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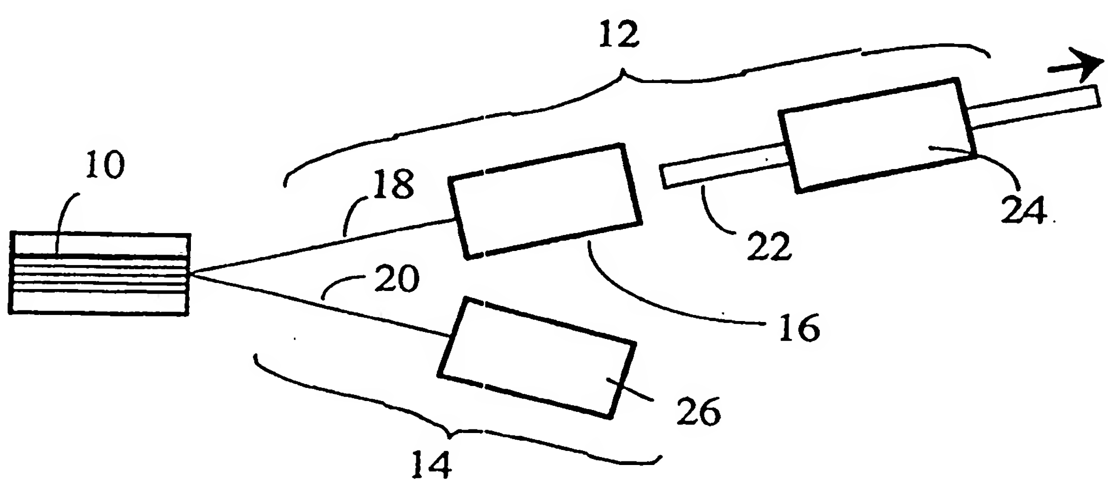

(57) Abstract

External cavity micro laser apparatus comprises at least one multimode micro laser (10) having multiple lasing lobe components. External cavity means embracing the laser (10) has an output section (12) including spatial filter means (22), which may be the input aperture of an optical waveguide (22), for effectively selecting at least one of the transverse lasing lobe components. The cavity output section (12) includes imaging means (16) for imaging at the spatial filter means (22) a far field spatial frequency distribution in the slow axis plane of the emission aperture, at which distribution the lasing lobe components are spatially distinguishable. A cavity return section (14) receives the amplified lasing lobe component after reflection from the laser. Return means (26) in the return section (14) efficiently returns to the laser means (10) at least a portion of the amplified and reflected lasing lobe component.

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EXTERNAL CAVITY MICRO LASER APPARATUS

FIELD OF THE INVENTION

This invention relates to external cavity micro laser apparatus wherein one or more multimode micro lasers (as herein defined) are efficiently coupled directly into the input aperture of an optical fiber or other optical waveguide.

BACKGROUND OF THE INVENTION

As used herein, the term "external cavity micro laser apparatus" means apparatus comprising multi-mode micro laser means (as herein defined) having an external cavity for accomplishing mode selection, mode mixing, frequency selection, pulse shaping, beam take-off, and the like.

As used herein, the term "multi-mode micro laser" (or "multi-mode micro laser means") is intended to mean lasing devices, typically but not necessarily of semiconductor construction, which are micro-miniature in size with dimensions typically measured in microns, which may produce one-dimensional or two-dimensional coherent, partially coherent or incoherent emissions, and which produce multiple modes each with multiple lasing lobe components. The term is intended to embrace what are today commonly known as "broad area lasers" or "BALs" which may have an aspect ratio of, *e.g.*, 50:1 to 400:1 (slow axis to fast axis ratio). The term encompasses "laser arrays" which comprise a series of spaced coupled or uncoupled emitters--either broad area lasers or standard lasers. The term also includes laser bars which may be up to a few centimeters wide, *e.g.*, which may contain an array of uncoupled BALs, or a two-dimensional stack of such laser bars. Typical broad area lasers have a single broad stripe for increased output power. Laser arrays have individual current stripes, one for each emitter, which may be closely spaced such that there is a strong mutual coupling or interaction between the light generated by the emitters. In practice, a laser array behaves similar to a broad area laser with respect to its modal properties, except that a laser array prefers to oscillate in higher order modes of order N,

where N is equal to the number of stripes or emitters. In a working system "N", for example, might have a value of 10.

An intense need exists for diffraction limited laser sources of several hundred milliwatts of output power for pumping optical fiber amplifiers in communication networks. Commercially available semiconductor lasers are capable of delivering high power, however, the need for an efficient and inexpensive means for coupling the semiconductor laser energy over a few hundred milliwatts into the input aperture of an optical fiber or other optical waveguide has not, prior to this invention, been satisfied.

There are two characteristics of output beams from micro lasers that make single mode fiber coupling inefficient. First, in the slow axis direction (major axis direction of the near field elliptic output beam), micro lasers support multiple transverse modes that are incoherent with respect to each other. Consequently, the output beam cannot be focused with near-diffraction-limited performance in this direction.

Second, the high ellipticity or high aspect ratio of the output beam cross section (typically greater than 1:100 at the near field) results in poor mode matching with the typically circularly symmetric modes of optical fibers.

SUMMARY OF THE INVENTION

In accordance with the present invention, the coherence of the output beam from such micro lasers is dramatically improved to make possible near-diffraction-limited imaging of the output beam into the input aperture of an optical fiber or other optical waveguide. In accordance with an aspect of the invention, means are provided for reshaping the aspect ratio of the output beam such that it conforms more closely to the aspect ratio of the input aperture of the coupled optical waveguide. In accordance with an aspect of the invention, the input aperture is employed as a spatial filter to select desired lasing lobe components of the output beam.

In order to obtain near-diffraction-limited performance in the slow axis direction, either the fundamental mode or a group of phase-locked higher order modes of the micro laser are excited by appropriate optical feedback. To achieve an approximately circularly symmetric spot size that matches the input aperture of the coupled optical waveguide, an appropriately designed coupling optics having an anamorphic component is employed.

BRIEF DESCRIPTION OF THE FIGURES

Figs. 1-4 and 4A illustrate a preferred embodiment of the invention. Figs. 1,3 and 4A are in-plane views -- that is views in the plane of the slow axis. Fig. 2 is a view in the plane of the fast axis. Fig. 4 is a perspective view.

Fig. 5 is a highly schematic view of optical waveguide input apparatus according to the present invention.

Fig. 6 shows alternative optical waveguide input apparatus.

Figs. 7-8 are perspective and side elevation views of yet another embodiment of waveguide input apparatus according to the invention.

Figs. 9-12 illustrate various anamorphic coupling optics which may be employed in the practice of the present invention.

Figs. 13-16 illustrate alternative embodiments of an execution of the invention utilizing transverse micro laser modes.

Figs. 17-19 illustrate embodiments of the invention employing micro lasers having one-dimensional and two-dimensional arrays of emitters.

Figs. 20-21 are fast plane (FIG. 20) and perspective (FIG. 21) views of an on-axis execution of the present invention wherein the fundamental mode of the micro laser is utilized.

Figs. 21A and 21B are tutorial views illustrating a mode mixing principle embraced by the present invention.

Figs. 22-28 illustrate various arrangements by which a fraction of output laser energy is returned to the micro laser for regeneration.

Fig. 29 schematically depicts a mode scrambler useful in the practice of the present invention.

Figs. 30-33 depict various beamlet despacing arrangements according to the present invention.

Figs. 34a and 34b are embodiments of the invention producing dual output beams.

Fig. 35 is an embodiment similar to Figs. 34a and 34b, having a second converging lens and a plane mirror.

Fig. 36 is an embodiment of the invention similar to Fig. 35, but including a saturable absorber.

Fig. 37 is an embodiment of the invention employing astigmatism-correcting optics.

Fig. 38 is an embodiment of the invention combining features from certain of the above-identified embodiments.

Fig. 39 is an embodiment of the invention employing frequency selection through the use of planar grating and stripe imaging mirror.

Fig. 40 is an embodiment of the invention employing alternative means for frequency selection.

Fig. 41 is an embodiment of the invention employing yet another frequency selection technique.

Fig. 42 is an embodiment of the invention employing an array of broad-area micro lasers.

Fig. 43 is an embodiment of the invention similar to Fig. 42, employing anamorphic optics for astigmatism correction in combination with a saturable absorber for pulse shaping.

Fig. 44a is an embodiment similar to Fig. 43, but having the output beam focused to a spot suitable for inputing into an optical fiber.

Fig. 44b is an embodiment of the invention employing a two-dimensional assemblage of broad area micro lasers.

Fig. 45 is an embodiment of the invention having imaging means in a spatial filtering plane.

Fig. 46 is an embodiment of the invention related to Fig. 45 and employing astigmatism-correcting optics.

Fig. 47 is an embodiment similar to the embodiment shown in Fig. 46, but employing a saturable absorber.

Fig. 48 is yet another embodiment of the present invention.

Fig. 49 is an embodiment of the invention similar to the embodiment of Fig. 45, but employing bulk optics.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Figure 1 is a highly schematic representation of external cavity micro laser apparatus according to the present invention which may include a micro laser 10. The micro laser 10 has an emission aperture (not shown in Figure 1) with a relatively long dimension lying in a slow axis plane and a relatively short dimension lying in a fast axis plane, the laser 10 producing multiple transverse lasing modes, the multiple modes having multiple lasing lobe components.

The apparatus of Figure 1 includes an external cavity embracing the micro laser 10. The external cavity has an output section 12 and a feedback or return section 14.

As will be described, the output section 12 includes a spatial filter for selecting at least one of the transverse lasing lobe components emitted by the laser 10 and imaging means or coupling optics 16 for imaging at the spatial filter a far-field spatial frequency distribution of the emission aperture at which the lasing lobe components are spatially distinguishable.

The output section 12 include an optical waveguide, here shown as an optical fiber 22, functioning as the aforesaid spatial filter, as will be described in detail hereinafter. The output section 12 also includes an output coupler 24 which includes feedback means for causing a fraction of

the optical energy in the selected lasing lobe components to be fed back to the laser means for amplification.

The return section 14 includes efficient return means 26 for returning at least a major portion of (ideally all of) the amplified and reflected lasing lobe component to the laser means. Lines 18, 20 represent the symmetry axes of the lobes excited by the external cavity laser apparatus. In general, the dominant mode component of both lobes belong to the same higher order laser mode.

As will be described in much more detail hereinafter, the imaging means or coupling optics 16 includes an anamorphic component which shapes the output lasing lobe component to be nearly circularly symmetric and nearly astigmatism free. The coupling optics 16 forms a waist of size close to the mode size of the fiber 22 for high fiber coupling efficiency. The location of the waist is at the in-plane focal plane for maximum mode discrimination, as will be explained. Also, this plane coincides with the out-of-plane image plane of the coupling optics 16.

Figure 2 is a view in the fast axis plane, and Figure 3 is a view in the slow axis plane, of the apparatus illustrated in Fig. 1, when the same coupling optics are shared by the output section and the return section.

In Figures 2-3, the micro laser is designated 28. The coupling optics is designated 28. The optical fiber is shown at 32 and the output coupler at 34. Figure 3 illustrates a linear or phase conjugating mirror 36 for efficiently returning the selected amplified and reflected lasing lobe component back to the laser 28.

Mirror 36 can be a dielectric thin film coated high reflector that has a constant reflectivity independent of the incident laser intensity. A phase conjugating mirror behaves in a nonlinear fashion in the sense the reflectivity depends on the incident laser beam intensity as a result of intensity dependence of the refractive index of the medium. For example, if the index slightly increases with the intensity, the incident and reflected

wave in the medium generates a standing wave intensity pattern which will result in an index grating in the medium. This index grating can further reflect the incident light resulting in a reflectivity that increases with incident light intensity. The reflected wave propagates in the opposite direction compared to the incident beam direction and is called a phase conjugate of the incident beam. It is well known that a phase conjugate beam travels through the same optical path the incident beam travelled and thus the reflected beam can correct for any phase distortions arising from index nonuniformity in the medium. A micro laser chip can have thermal induced as well as crystal defects induced nonuniformities and a phase conjugating reflector can correct for phase distortions caused by such inhomogeneities.

A phase conjugating mirror can improve the overall spatial coherence of the output or it can help phase-lock the uncoupled emitters in the micro chip laser. However, a phase conjugating mirror has relatively lower reflectivity compared to the dielectric multilayer coated mirrors resulting in relatively low efficiency of the laser apparatus. Hence, a phase conjugating mirror is recommended only for those demanding applications where satisfactory coherence performance may not be obtained with dielectric mirrors. Both dielectric mirrors and phase conjugating mirrors are available from many vendors.

The array-to-array feedback optics in the return section 14 efficiently feeds back the reflected lasing lobe component into the micro laser. The feedback optics images the laser emission aperture back upon itself with unity magnification and without significant loss of power. The selected lasing lobe component (coming in from the fiber) is coupled into the laser, gets amplified and forms a bright spot on to the mirror 36. The mirror 36 is placed in the same plane as tip of the fiber 32. The position of this spot and the fiber tip lie symmetrically opposite about the laser optical axis and in a plane perpendicular to the laser axis. This bright spot

is reflected back by mirror 36, gets coupled and amplified in the laser 28 much more strongly and forms a powerful output beam. The output beam couples into the fiber 32 with high efficiency. The Figs. 1-4 arrangement is somewhat insensitive to small in-plane misalignments of the fiber, however, there should be an optimum position for the maximum output for a given drive current.

When coupling optics in both the return section and the output section are not shared, the location and shape of the mirror 36 is such that the reflector's curvature matches the curvature of the impinging optical wavefront. The feedback optics may be as simple as a spherical mirror that combines the necessary imaging elements, and the highly reflective mirror 36. As will be described, to reduce the total number of components in the apparatus, the feedback optics may share optics with the output section 12.

The resonant external optical cavity is formed by the mirror 36 in the return section 14 and partially reflective means (to be described) in the output coupler 34 (24 in Figure 1).

Figure 4 is a perspective view of the apparatus illustrated more schematically in Figures 1-3. Figure 4 illustrates a micro laser 38 having an emission aperture from which laser energy is emitted. In Figure 4 an optical waveguide is shown at 42 and an output coupler is shown at 44. Figure 4 illustrates a mirror 46 in the return section. The coupling optics in the Figure 4 geometry comprises anamorphic lens means, here shown as a cylinder lens 48, and non-anamorphic lens means 50 (which may be a spherical, aspheric, ball, or graded index lens). The anamorphic lens 48 collimates the beam 52 in the out-of-plane direction. Figure 4 illustrates, like Figs. 1-3, a higher order (non-fundamental) mode operation.

The focal length of the anamorphic lens 48 is such that the out-of-plane beam spread is roughly equal to the in-plane beam width (the width of the micro laser active region or emission aperture 40). The focal length

of the non-anamorphic lens 50 is such that it forms a waist of a size that is substantially equal to the spot size of the input aperture of the waveguide 42.

In the fast axis direction (the vertical direction in Fig. 2), the near-field beam full-width at half maximum (FWHM) is about one micron and the beam divergence is typically about 35 to 40 degrees FWHM as the beam leaves the laser emission aperture. Also, in this direction, the laser supports only a single transverse mode and consequently the beam has high spatial coherence. Therefore, in this direction, the beam can be focused to a diffraction limited spot of size substantially equal to the coupled fiber spot size by using well corrected coupling optics. Commercially available micro lasers come with 95% back facet reflectivity and 5% front facet reflectivity. They are distributed by number of manufacturers including Spectra Diode Labs (San Jose, CA) and Semiconductor Laser International Corporation (Endicott, NY).

The present invention may be employed with a laser whose front facet reflectivity is of the order of few tenths of a percent. Antireflection coatings to yield such low reflectivity can be custom made by the manufacturers. For sufficiently small distances, the laser output beam in the slow axis plane can be considered collimated (because of the low divergence angle of 0.5% degree, e.g.), but divergent (35-40 degrees, e.g.) in the fast axis plane. Appropriate anamorphic coupling optics that has different focal lengths in the fast-axis and slow axis directions may be chosen to obtain a circular spot that is equal to the spot size of the fundamental mode of the fiber (typically 6 microns for commercially available Corning flexcore single mode fiber, or typically the core diameter for a multimode fiber).

An important advantage of the Figs. 1-4 configuration is that it provides a non-beam-steering waveguide coupled output. Beam steering (as drive current changes) in a free running micro laser is dependent upon

changes in refractive index of the laser active medium due to: 1) drive current variations and 2) drive-current-induced temperature changes (thermal lensing). Since the angle of refraction depends upon the refractive index, the beam steers with the index changes (for an incident beam at a constant angle of incidence).

Beam steering effects are difficult to eliminate completely from most injection locking and external cavity schemes. For some of the known external cavity schemes, beam steering manifests as a reduction of output power below the expected value. In Fig. 3, beam steering simply changes the position of the spot on the external mirror (36 in Fig. 3) in the in-plane direction. Since this spot is a real image of the fiber tip, according to the reciprocity theorem a real image of this spot is formed back on the fiber tip and is coupled into the fiber. Thus the Figs. 1-4 embodiment is compensated for any thermal lensing or drive-current-induced index changes that may be present.

Figures 1-4 illustrate the feedback or return optics in the return section schematically. In commercial practice, the return mirror (46 in Figure 4), which can be a non-linear phase conjugating mirror, due to the small angle subtended by the output and return beams (represented by lines 18, 20 in Figure 1), will be closely adjacent to the input aperture to the optical waveguide.

As discussed above, in accordance with an important aspect of the present invention, an optical waveguide, shown in Figs. 1-4 as an optical fiber, functions as a spatial filter.

In the microlaser apparatus according to present invention, imaging means are provided for imaging at the input aperture of an optical waveguide a far field spatial frequency distribution of the emission aperture of the microlaser at which lasing lobe components are spatially distinguishable. As will be described, the input aperture of the optical

wave guide is sized an positioned to select one or more predetermine lasing lobe components.

Fig. 4A is a view which depicts the manner in which spatial filtering of selecting laser lobe component(s) is achieved in accordance with the present invention. Fig. 4A illustrates a geometry similar to that shown in Figs. 1-4, comprising a micro laser 41, an optical waveguide 43 having a cladding 45 and a core 47, and imaging means shown in the form of an anamorphic lens 49 and a non-anamorphic lens 51. A high reflectivity return mirror is shown at 53. Partially reflective means 55 returns a predetermined fraction of the output beam back to the micro laser 41, as described herein.

It is noted that each broad-area mode may be closely approximated to have a sinusoidal mode shape in the near field. One can visualize that each of these modes is constructed by an interference of an up-propagating (in Figure 4A) plane wave and down-propagating plane wave making an appropriate small but equal angle with laser axis 57. (Interference of two plane waves gives a sinusoidal profile). Up-propagating wave forms an upper lobe and down-propagating wave forms a lower lobe in the far field. Thus, each mode forms a double-lobed pattern in the far field (except the fundamental mode which forms a slightly broader single-lobed pattern). In Fig. 4A, lobes of mth mode and their adjacent mode lobes (m+1, m-1) are shown.

Lines 59 represent symmetry axes of broad-area mode lobes. Even though the lobes appear spatially isolated in the figure, there is considerable overlap between adjacent lobes and the overlap is a minimum at the Fourier plane (in-plane focal plane where the waveguide input aperture is placed). Fig. 4A shows selection of the mth mode lobe by the waveguide aperture. The (m+1)th mode lobe and (m-1)th lobes experience a much higher loss compared to the mth mode lobe. Note that when mth mode lobe is lasing,

the laser supports a nearly coherent superposition of a group of modes around the mth order mode.

Figure 5 schematically illustrates fiber input apparatus comprising a highly reflective return mirror 54 located laterally spaced from but contiguous to an optical waveguide 56. The waveguide 56 has a cladding 58 and a core with an input aperture 62.

Figure 6 illustrates another embodiment of fiber input apparatus comprising a ferrule 66 which supports an optical fiber 70 having a core 72 with an input aperture 68. A portion 62 of an end surface 64 of the ferrule 66 is mirrorized or otherwise made reflective to constitute the return mirror (46 in Figure 4, for example).

In the Figure 6 arrangement, the ferrule 66 may, for example, be .1 inch in diameter and may be composed of a ceramic material. The portion 62 may have a multilayer dielectric coating to create a highly reflective mirror surface.

The fiber 70, which may for example be 125 micro meters in diameter, is located on a facet of the ferrule 66 end surface 64 which is angle polished or anti-reflection coated to suppress reflections off the ferrule and fiber end surfaces back into the micro laser.

Figures 7-8 illustrate yet another return mirror arrangement. In Figure 7-8 a ferrule 76 has a dual facet chisel-shaped termination, with a fiber 78 being located in one facet 80 slightly offset from an edge 82 formed at the convergence of facet 80 and the adjacent facet 84. The facet 80 and the face of the embedded fiber 78 are preferably formed at the Brewster angle for a maximized transmission into the optical fiber 78 and minimized reflection losses.

On the opposed facet 84 of the ferrule is positioned a wedge 86. The wedge 86 has a reflective surface 88 which constitutes the return mirror (46 in Fig. 4 for example). As discussed above, preferably the plane of the reflective surface 88 includes the input aperture of the core of

the optical fiber 78. In order to achieve such coplanarity of the reflective surface 88 and the input aperture of the core of the fiber 78. the wedge 86 may be adjusted in position along the sloping facet 84 and secured thereon when coplanarity is achieved.

In Figure 8, line 90 represents the optical beam in the return section being reflected back to the laser. Line 92 represents the optical beam in the output section which enters the fiber 78 to provide a useful output from the system. Energy reflected off the face of the fiber 78 and ferrule 76 is represented by line 94. This energy may be employed as a monitoring beam to monitor the location and other parameters of the output beam.

The input aperture of the output optical fiber receives an output laser beam from the micro laser. The emission aperture of the micro laser means has a near field distribution with a high aspect ratio, whereas the input aperture of the optical waveguide is more circularly symmetric. The imaging means in accordance with the present invention, as noted, has an anamorphic component for reshaping the elliptic beam distribution to better conform to the typically circular input aperture of the optical fiber core. In Figs. 8-9, wedge 86 may be positioned on the opposite slopping side 80 of the ferrule 76.

Whereas any of a number of geometries may be employed, as will be described below, certain general principles of the coupling optics employed in the practice of the present invention will now be described.

Figs. 9 and 10 illustrate coupling optics as comprising a anamorphic lens 77 and a spherical lens 79. In Figs. 11-12, two anamorphic lenses 81, 83 of different power are employed. The anamorphic lens 77 may, e.g., be graded index cylinders or aspheric rods to minimize spherical aberration. The anamorphic lenses 77, 81 should have a high numerical aperture above 0.5. All lens surfaces should ideally be anti-reflection coated. The spherical lens 79 may alternatively be an aspheric lens, ball lens, gradient index lens, or any other combination of diffractive and

refractive optical elements. The out-of-plane object plane and image plane of the lens combination coincides with in-plane focal planes of the combination. The focal lengths of the lenses are chosen such that a nearly circular spot whose size matches with the modal spot size of the fiber, is formed at one of the in-plane focal planes. The in-plane spot size of the output beam at the fiber input face may be optimized to account for the near-diffraction-limited performance in this plane.

In the Figs. 9-10 combination (anamorphic and spherical), the anamorphic lens 77 first collimates the beam in the fast axis direction to a beam size comparable to the array aperture. The lens 79 focal length is chosen such that the focused spot has the same size as the waveguide spot size. All the lens surfaces are antireflection coated to 0.1% reflectivity. Anamorphic lenses are available from Doris Lens, Inc., Quebec, Canada, for example. Spherical lens 79 is available from many vendors. In the second combination, two anamorphic lenses can be used, one for each axis (fast axis and slow axis) so that a circular spot is formed at the fiber face. The advantage of the Figs. 11-12 geometry is that the size of the spot can be controlled independently in both axis by adjusting the axial positions of the lenses 81, 83 relative to the array. However, the disadvantage is that the lens 83 can introduce additional spherical aberration in the out-of-plane direction. The Figs. 9-10 combination does not introduce aberrations because well-corrected spherical lenses are readily available.

Figures 13-16 illustrate alternative embodiments of the invention involving different arrangements of the optics in the output section and the return section to achieve the afore-described objectives of the invention.

Specifically, the Figure 13 embodiment is similar to the Figure 4 embodiment described above, with the exception that the relative positions of the anamorphic lens means and the non-anamorphic lens means is interchanged.

Figure 14 is related to the Figure 13 embodiment, however in the Figure 14 arrangement the return mirror 96 may be a spherical mirror having a curvature equal to its distance from the focal plane of a non-anamorphic lens 102. The anamorphic lens component in the system is a cylinder lens 104 in the output section whose position and focal length is chosen such that an astigmatically corrected circular beam with waist size equal to the fiber spot size is formed at the image plane of the non-anamorphic lens 102.

Figure 15 illustrates external cavity micro laser apparatus according to the invention comprising micro laser 106, optical fiber 108, and coupling optics in the form of a truncated imaging mirror 110. An anamorphic lens 112 encompasses only the output section, and a second anamorphic lens 114 at 90 degrees relative to lens 112 influences the output beam in the in-plane direction.

Thus the array-to-fiber coupling optics consist of two crossed anamorphic lenses 112, 114. The focal lengths and positions of the anamorphic lenses 112, 114 are chosen such that the beam is corrected for astigmatism and forms a nearly circular waist of size substantially equal to the fiber spot size.

An auxiliary plane mirror 116 functions as the cavity boundary in the return section. A real image of the emission aperture 117 of the micro laser 106 is formed on the plane mirror 116 by the imaging mirror 110 in order to increase the tolerance for component alignment. Alternatively, the plane mirror 116 may be eliminated and the imaging mirror 110 may be reoriented to form a real image of the emission aperture 117 of the micro laser 106 upon itself.

In Figure 15, the elongated shape of the lasing lobe as it impinges on the imaging mirror 110 is shown at 118. The shape of the lasing lobe at the anamorphic lens 112 is shown at 120. Fig. 16 schematically illustrates yet another embodiment of the invention wherein an anamorphic

lens 124 is disposed adjacent a micro laser 126 such as to correct the astigmatism in the output beam from the laser as the beam reaches an imaging mirror 128. As the output beam is astigmatism-corrected, a spherical lens 130 may be employed in lieu of the anamorphic lens 114 utilized in the Figure 15 arrangement.

The Fig. 16 arrangement includes optional pulse shaping means, here shown as a saturable absorber 132 located adjacent the plane of a plane mirror 134 in the return section corresponding to the plane mirror 116 in the Figure 15 arrangement. It should be understood that pulse shaping means such as a saturable absorber may be employed in any and all of the embodiments illustrated herein in applications wherein beam pulse shaping is desired.

Figure 17 schematically depicts an embodiment of the invention similar to Figure 4, but illustrating that the invention may be used with an array of uncoupled emitters 136. Off-axis power extraction is shown. For on-axis power extraction, as will be described in connection with Figures 20-21, the return mirror 138 is removed and the angle-polished (or anti-reflection-coated) fiber 140 is brought to the array axis 142. The distance of the fiber face 144 from the axis determines the dominant mode component of each of the laser. If the fiber selects the fifteenth mode of the first emitter, for example, the same fifteenth order mode is selected for all other lasers.

Figure 18 illustrates yet another embodiment of the invention which is related to the Figure 17 embodiment but differs in two respects. The micro laser is shown as having a two dimensional stack of emitters 148. It should be understood from the definition of "multimode micro laser" or "multimode micro laser means" set forth above that those terms encompass not only single emitters, but linear arrays of uncoupled emitters as well as two dimensional arrays or stacks of coupled and uncoupled emitters. In the Figure 18 embodiment, as opposed to the Figure 17 embodiment, for

example, the anamorphic lens which serves the entire array of micro emitters 136 is eliminated and individual anamorphic lenslets 146, one associated with each emitter 148, collimates the output of the emitter in the fast axis plane (out-of-plane direction). This produces a nearly uniform parallel beam of light in the vertical direction (fast-axis plane. Thus the effect of the discontinuity of the emitters in the vertical direction is reduced. Further, the compactness of the overall system is improved.

Figure 19 is an in-plane view of an embodiment for extracting output power from the fundamental mode of a multimode micro laser means.(Please revert to Figure 2 for an out-of-plane view which is the same for both transverse mode and fundamental mode executions.) In Figure 19 a multimode micro laser is indicated at 152; an optical fiber is shown at 154. Coupling optics are shown at 156. In Figures 19 and 20 the solid lines represent beam profiles (locus of half-maxima points of the beam). Dashed lines represent a possible beam profile within the coupling optics which can be parallel or non parallel depending on the elements in the coupling optics.

The coupling optics should be designed such that a circular spot of size that matches with the spot size of the modes of the fiber is formed at the in-plane focal plane of the coupling optics for the best laser mode discrimination. The fiber input aperture is placed at the in-plane focal plane which coincides with the out-of-plane image plane. The laser emission aperture is placed at the other in-plane focal plane which coincides with out-of-plane object plane.

Fig. 19 shows the in-plane view (plane normal to the fast axis) wherein the beam width is equal to the width of the current stripe or aperture size. Typically, micro lasers with aperture size from 50 microns to 1 cm are available commercially. For an array with 100 micron stripe width, the diffraction limit corresponds to about .5 degree. However, because of the multimode oscillation a divergence of about 10 degrees (20

times the diffraction limit) is typical. With an appropriate feedback from the output fiber, this divergence can be reduced to a near-diffraction limit (less than twice the diffraction limit) and focused to a spot size that is substantially equal to the fiber spot size. This configuration excites the fundamental mode of the array and hence it may be called "on-axis excitation". This is the simplest scheme. However, off-axis excitation has significant advantages in terms of far-field lobe broadening. When a micro laser is used to amplify a beam of light, the gain of the array induces a broadening of its far field lobe. The greatest broadening is for the on-axis beam, which means that an on-axis beam diverges the greatest. For an off-axis beam the gain-induced broadening is less. The dominant mode component for the on-axis beam is the fundamental mode. Due to gain-broadening, the FWHM of the fundamental mode lobe has the largest value (3-4 times the diffraction limit) and it approaches the diffraction limit at higher order mode lobes. Even though for diffraction-limited performance the array should be operated off-axis, there is a disadvantage. The radiation loss of the laser modes increases with mode number, thereby reducing the effective amplification of the off-axis beam. Due to these competing effects, there is an optimum angle for amplification, which has been shown to exist experimentally. Therefore, in many situations, off-axis excitation scheme may extract a higher output power than the on-axis scheme. When multimode fibers are used, diffraction-limited-performance is not critical, and consequently on-axis schemes may prove to be simpler.

Figure 20 is a perspective view similar to Figure 19, but showing more specifically the coupling optics as comprising an anamorphic lens 158, followed by a non-anamorphic lens 160. The Figure 20 arrangement excites predominantly the fundamental mode of micro laser 164. The spatial filtering output waveguide, here shown as a fiber 162, is placed at the in-plane focal plane of the anamorphic coupling optics. A nearly circular waist (spot) that matches the fiber spot size is formed at this plane

so that the output laser light from the micro laser 164 is efficiently coupled into the fiber 162.

The spatial filtering output fiber 162 is placed at the in-plane focal plane of the anamorphic coupling optics 158, 160. This plane also coincides with the out-of-plane image plane of the coupling optics. A nearly circular waist (spot) that matches the fiber spot size is formed at this plane so that the light is efficiently coupled into the fiber 162.

Figure 21 is yet another embodiment similar to Figure 20, but, as in the Figure 18 embodiment, having the full-beam anamorphic component substituted by an array of anamorphic lenslets, one lenslet for each of the emitters in the two-dimensional stack of emitters constituting the micro laser means.

As described above, the external cavity micro laser apparatus according to the present invention has as an important aspect partial reflecting means located beyond the waveguide input aperture and constituting a boundary of the cavity for returning a predetermined fraction of the optical energy in the waveguide means to the laser means.

By returning a predetermined fraction of the optical energy in the waveguide to the laser means, selected lasing lobe components are mixed in the waveguide between the input aperture and the partial reflecting means such that the coherence and the imaging performance of the imaging means is improved.

Figs. 21A and 21B illustrate the improved mode mixing which results from an output coupler 169 placed beyond the input aperture of the fiber (Fig. 21A) compared to a partial reflector placed at the input face of the fiber (Fig. 21B). Fig. 21A illustrates a system similar to that in Fig. 20 comprising a microlaser 169 (here shown as an array of uncoupled emitters labeled 1-5), an output coupler 181, and a waveguide comprising cladding 183 and a core 185. Imaging means are shown in the form of an anamorphic lens 187 and a non-anamorphic lens 189.

Fig. 21B differs from Fig. 21A in that the output coupler 181 is eliminated and the input aperture of the fiber core 183 has on its face a partial reflector 191. In Figs. 21A and 21B the waveguide is shown as an optical fiber, by way of example. The partial reflector 191 in Fig. 21B is assumed to have the same size and shape as the fiber core. The fiber is assumed to have a numerical aperture sufficiently high to accept light even from the extreme emitters 1 and 5. A single mode fiber and fundamental mode excitation are assumed in this example.

In Fig. 21A, since the feedback is coming within the fiber, light from individual emitters are indistinguishable in terms of propagation direction. Hence, each emitter sees light from all other emitters which makes it easier for all of the emitters to lock in phase to a single common frequency. However, in Fig. 21B, if we were to take the feedback right from the fiber emission aperture using an apertured mirror, perfect mode mixing is not possible. The laws of reflection (incident ray and reflected ray makes same angle with the normal) favors emitter 1 to be coupled to emitter five and visa versa more strongly than their coupling to other emitters. Similarly, emitters 2 and 4 couple strongly to each other and weakly to others. Because of the symmetry, emitter 3 couples back to itself strongly and weakly with others. Hence the emitters in Fig. 21B do not communicate among one another as effectively as the emitters do in Fig. 21A and therefore the coherence performance will be inferior.

A few of the many available structures for accomplishing the partial reflection of optical energy to the laser means will now be described. An output coupler arrangement is illustrated in Figure 22 as comprising a lens 172 (here shown by way of example as a graded index lens) disposed in a break between a first length 174 of optical waveguide receiving optical energy from a laser, and a second length 176 of optical waveguide. A ferrule 178 terminates the fiber length 174. In the Figure 22 embodiment, the partially reflective surface is a cleaved and polished surface 180 which

will provide, for example, approximately 4% Fresnel back reflection. The surface 180 may contain a reflection coating to achieve any desired level of reflectivity.

The lens 172 which may be collects the light from the waveguide core 182 within waveguide length 174 and focuses it into the core 184 of fiber length 176.

Figure 23 illustrates an output coupler arrangement wherein the partially reflecting means provides a Bragg grating 186 in the waveguide 188. The Bragg grating 186 may be written on the core of a silica-based fiber using a high power ultraviolet source such as an excimer laser. A Bragg grating 186 can be designed to have back reflectivities ranging from a few percent to 99 percent, and a wavelength reflection band from .1 nanometers to several nanometers on any desired wavelength.

When a multimode fiber is used, Bragg grating of a specific length can fill in the entire core of the fiber. In this case, all of the modes in the fiber will be equally affected by the grating. On the other hand, Bragg grating can be localized around the axis of the core and fill in the core only partially. Only those modes that spatially overlap with the grating would be reflected. Gratings can be prepared any number of ways using standard grating writing techniques. If the grating is localized near the axis, only the lower order modes will be reflected back for amplification in the microlaser. Thus, only those modes will be predominantly amplified and coupled back into the fiber. This arrangement would help to efficiently couple light into the fiber even if there are any inhomogeneities or scattering present in the microlaser medium. Small amounts of inhomogeneities and scattering tend to couple light into higher order fiber modes, but those would still be coupled efficiently into the core of the fiber.

In an output coupler alternative illustrated in Figure 24, laser light in waveguide 190 is collimated by a lens arrangement 192 and frequency

dispersed by a grating 194. A mirror 196 returns incident laser light to the optical waveguide 190 for return to the laser means. The band of optical frequencies desired to be returned to the laser means and amplified is selected by adjusting the tilt angle of the mirror 196. The main optical output from the system is indicated at 198.

Yet another optical coupler arrangement is shown in Figure 25 wherein an optical waveguide 200 is looped back upon itself to form a non-linear or linear "Sagnac" reflector serving as the partial reflecting means.

The Figure 25 optical coupler includes in the region of the loop 208 a polarization controller 210 for controlling the predetermined fraction of laser energy returned to the laser means and its plane of polarization. Also, the Figure 25 optical coupler may include an optional optical isolator 209 for eliminating any interference effects of the clockwise and counter clockwise beams in the loop 208.

Figure 26 depicts yet another optical coupler geometry which combines certain of the features in Figs. 24 and 25 couplers. The Figure 26 arrangement includes both a fiber coupler 212 and a grating 214, preferably of the Littrow type. The fiber coupler 212 provides alternative outputs from the system. The predetermined fraction of laser energy which is returned to the laser means is determined by the properties of the fiber coupler 212 and the diffraction efficiency of the grating 214.

Figure 27 illustrates an optical coupler arrangement in which an output optical waveguide is divided into a first length 220 and a second length 222. A lens 224 collects light from the first length of fiber 220 and focuses it upon a saturable absorber 226. A second lens 228 collects light modified by the absorber 226, and focuses it into the input aperture of the second length 222 of optical waveguide. As explained elsewhere herein, pulse shaping can be accomplished in any of the geometries described herein, using any of the well-known pulse-shaping techniques. A saturable

absorber is but one of a number of devices and techniques which may be utilized to accomplish pulse shaping.

Figure 28 illustrates an alternative optical coupler arrangement which is similar to that shown in Figure 27, with a high reflection mirror 216 substituted for the grating 214 in the Fig. 26 embodiment. To again illustrate that pulse shaping can be accomplished in any of the geometries described herein, a saturable absorber is illustrated at 218, disposed adjacent the plane of the mirror 216.

Thus, in accordance with the present invention there is provided external cavity micro laser apparatus in which a self mode-discriminating waveguide-coupled mode-matched cavity extracts high brightness laser light from multimode micro laser arrangements which may comprise either a single emitter, a linear array of emitters, or a two-dimensional stack of emitters. The input aperture of the coupled waveguide is placed at the spatial filtering plane of the micro laser and is used as the mode-discriminating element. Feedback reflection from inside the fiber core acts as the mode discriminating feedback necessary to extract high brightness power from the micro laser. The above-described embodiments of the present invention are insensitive to beam steering as laser drive current is varied in the micro laser, and are capable of phase locking uncoupled micro laser emitters.

Other modifications and embodiments of the invention may be apparent to those skilled in the art in view of the foregoing description. This description is to be construed as illustrative only and is for the purpose of teaching those skilled in the art the best modes for carrying out the invention. By way of example, mode scrambling means may be located in advance of the waveguide input aperture to enhance the mixing of the spatial modes of the waveguide means. Fig. 29 illustrates mode scrambling means in the form of a periodic micro-bend generator 230. The micro-bend generator 230 comprises micro-bend inducers 232, 234 having

internal serrations 236, 238, respectively, which capture an optical waveguide, here shown as an optical fiber 240.

At each micro-bend site, a fraction of the power in one mode is radiated (coupled) to other modes. Also some power is radiated out (coupled to radiation modes) and thus lost from the fiber core. By applying an appropriate small pressure in the direction shown by arrow 242 between the micro-bend inducers 232, 234, the severity of the micro bend in the fiber 240 can be adjusted and thus the mode mixing optimized with a tolerable radiation loss.

In the multimode fiber case, it may be especially desirable to have a mode scrambler for improved performance. In all of the embodiments discussed herein, an optical isolator located after the optical coupler (outside the cavity) improves the performance, as any unwanted reflections coming from beyond the output coupler are effectively isolated or attenuated.

Yet another modification of the invention is illustrated in Figure 30. Figure 30 illustrates micro laser apparatus comprising a laser array 246 having a plurality of spaced laser emitters 248, 250, 252, 254, 256, and 258 arranged in a linear array along a slow axis of the laser array 246. The emitters emit a like plurality of laterally spaced parallel beamlets 260, 262, 264, 266, 268, and 270. An anamorphic lens means 272 is provided for collimating the beamlets in the fast axis direction (perpendicular to the plane of Figure 30).

Despacing means 274 optically coupled to the laser array 246 is provided to reduce the spacing between the beamlets while preserving their parallelism to form a more tightly bundled output beam 276.

In the Fig. 30 embodiment of the invention the despacing means 274 comprises a parallel arrangement of beamlet-translation elements, which may, for example, comprise a stack of slides (glass, e.g.) 278, 280, 282, 284 and 286 of a number at least equal to N minus one, wherein N is the

number of emitters. Each of the slides is arranged at a common angle with respect to its respectively associated beamlet, the slides being constructed and arranged to progressively offset the beamlets into a state of contiguous parallelism. In a preferred arrangement, the angle "A" subtended by a normal to be impinged surface of the slide (for example, surface 288 on slide 286) and the impinging beamlet (268 in the case of the slide 286) is the Brewster angle.

In the preferred arrangement illustrated in Fig. 30, each of the slides has a beveled front face effective to prevent interference with an adjacent beamlet. In Figure 30, this beveled surface on slide 288, for example, is indicated at 290.

Figure 31 depicts an alternative form of the afore-discussed despacing means according to the invention. The Fig. 31 arrangement is similar to the Fig. 30 embodiment except that the slides, numbered collectively 291, have an angle "B" and a fully beveled front face 289. The Fig. 31 embodiment produces output beamlets 287 which are parallel and contiguous but not completely merged, as in the Fig. 30 embodiment. Figure 32 depicts despacing means similar to that shown in Fig. 30, except that beam-translation elements -- again here shown by way of example as slides 293, 295 -- are inverted in a mirror image relationship to slides 297, 299, and 301 such that the resulting merged output beam 305 is more nearly centered relative to the laser array 246 than is the case in the Fig. 30 embodiment.

Figure 33 illustrates yet another embodiment of the afore-described despacing means. Figure 33 illustrates micro laser apparatus comprising a laser array 292 similar to the laser array 246 illustrated in Figure 30, producing parallel beamlets 294, 296, 298, 300, 302, and 304. The Figure 33 embodiment of the despacing means includes a number of prisms 306, 308, 310, 312, 314, and 316 respectively associated with the emitters producing the beamlets. The prisms are constructed and arranged to

redirect the respectively associated beamlets into a state of contiguous parallelism in an output beam 320.

An anamorphic lens means 316 collimates the beamlets in the fast axis direction. A non-anamorphic lens 318 may couple the output beam into the input aperture of an optical waveguide.

Figs. 34-49 illustrate a set of embodiments of the invention in which the spatial filtering and selection of desired lasing lobe component is achieved using an angled prism wedge or a knife-edge instead of an optical fiber as in the above described embodiments. For certain applications, a fiber coupled output is not required. Besides, if the laser power is too high, a fiber may not be able to transmit the laser power efficiently because of the limited power transmitting capacity of an optical fiber arising from the optical nonlinearities present in the fiber medium. In the embodiments depicted in Figs. 34-49, the output can be taken out into free space without the need for a well aligned optical fiber or astigmatism correction. However, in the embodiments described in Figs. 34-49, it is possible to correct for astigmatism or couple into an optical fiber if necessary but not essential for the operation of the laser apparatus. A spatial filtering wedge or knife edge is required for spatial filtering and lasing lobe component selection.

Figs. 34a-34b comprise a multimode micron laser 356, which may be a one-dimensional emitter or a two-dimensional stack of emitters, and an external cavity 357. A focusing lens 358 images the emission aperture of laser 356 upon an imaging mirror 360. A spatial filter 362, serving also as an output coupler or a take-off mirror, is composed of a light transparent medium 364 and has an angled knife-edge surface 366. A partially reflective coating 368, on the surface 366 causes the output beam 370 to be divided, part being refracted through the light-transparent medium 364 of the spatial filter 362 to form a first output beam 372. A second part of the

output beam 370 is reflected from the coating 368 to form a second output beam 374.

The spatial filter 362 thus serves doubly as a take-out means or output coupler, forming the two output beams 372, 374. The output beams 372, 374 will be elliptical or otherwise elongated at the point of their convergence in the slow axis plane. Either of the beams 372, 374 may serve as a useful output or may be used as a means for monitoring the location and other characteristics of the other output beam on the angled knife-edge surface 366. The center of curvature of the imaging mirror 360 coincides with the operative edge 376 of the angled knife-edged surface 366.

Fig. 35 depicts another embodiment of the invention which is similar to the Figs. 34a-34b embodiment, with the exception that the imaging mirror 360 in the Figs. 34a-34b embodiment is replaced by a converging lens 380 and plane mirror 382. To adjust the position of the reimage at the spatial filter 384 of the selected lasing lobe component, the distance between the system optical axis 384 and the axis 386 of the converging lens 380 is set at a predetermined distance effective to place the said reimage in the appropriate location relative to the operative edge 388 of the knife-edge surface 390.

Second, rather than focusing lens 392 being constructed and positioned to image the emission aperture or facet of the laser array 394 at the plane mirror 382, the focusing lens 392 is preferably spaced a focal distance away from the emission aperture of the laser array 394 so as to collimate the output of the laser array in the fast axis plane. The combination of the converging lens 380 and the converging lens 392 images the emission aperture of the laser array 394 upon the plane mirror 382. In other respects, the Fig. 35 embodiment is similar to the embodiments discussed above.

The Fig. 36 embodiment is similar to the Fig. 35 embodiment except that it is caused to have pulse shaping capability by placement of a saturable absorber at the location of the image formed on the plane mirror 398. As is well known, a saturable absorber has the property of absorbing light having an intensity below a predetermined threshold, and transmitting with efficiency light received having an intensity above the said intensity threshold. The effect is to suppress the skirts of an incident pulse and thereby sharpen the pulse.

Fig. 37 illustrates yet another embodiment of the invention which is generally similar to the Figs. 34a-34b embodiment, but which has a number of significant modifications. In the Fig. 37 embodiment, a converging lens 404 is spaced a focal distance away from the laser 406, and an anamorphic lens, here shown as a cylinder lens 408, is disposed between the laser array 406 and the converging lens 404. The cylinder lens 408 collimates the beam in the fast axis plane.

The combination of the cylinder lens 408 and the converging lens 404 is such that the beam waist in both orthogonal planes is located at the operative edge 410 of the spatial filter take-out mirror 412. The cylinder lens 408 thus corrects for the astigmatism present in the Figs. 34a-34b embodiment such that the output beams 414, 416 are converged to a point image in the vicinity of the spatial filter-take out mirror 412 suitable for introduction into an optical fiber or the like.

The Fig. 37 embodiment also includes frequency dispersive means, here taking the form as a grating integrated with the concave imaging mirror 418. The grating mirror 418 has the effect of frequency dispersing in the orthogonal fast axis plane the reimage of the selected lasing lobe component which is formed at the spatial filter-take out means 412 by the grating mirror 418. By the expedient of using a frequency dispersive imaging mirror, with the apparatus of the invention a predetermined band

of lightwave frequencies in the selected lasing lobe component may be selected.

It is noted that the Fig. 37 embodiment differs from the Figs. 34a-34b embodiment in that to frequency select, grating-mirror 418 is translated along the fast axis in the manner in which the converging lens 380 is translated along the slow axis in the Fig. 35 embodiment. As described above in connection with the forgoing embodiments, the center of curvature of the concave grating-mirror 418 is at the operative edge 410 of the spatial filter take-out mirror 412.

Fig. 38 depicts an embodiment of the invention which combines the translated converging lens depicted, for example, in the Fig. 35 embodiment, the saturable absorber of the Fig. 36 embodiment, and the anamorphic lens described in connection with the Fig. 37 embodiment.

Fig. 39 illustrates an embodiment of the invention comprising, in general terms, multi-mode micro laser means having an emission aperture with a relatively long dimension lying in a slow axis plane and a relatively short dimension lying in a fast axis plane, the laser means producing multiple transverse lasing modes in said slow axis plane, said multiple transverse modes having multiple lasing lobe components. Spatial filter means are located in a spatial frequency plane corresponding to the emission aperture plane for effectively isolating at least one selected lasing lobe component in the slow-axis plane. Frequency selection means includes means for frequency dispersing the selected lasing lobe in the fast axis plane, and means for selecting in the desired lasing lobe component a predetermined band of lightwave frequencies for return to the laser means.

Specifically, in the Fig. 39 embodiment, the frequency dispersive means is shown as comprising a reflective plane grating 426 positioned between a laser 428 and an imaging mirror 430. To achieve frequency selection in the Fig. 39 embodiment, the imaging mirror 430 is modified to include a reflective stripe 432 which is sized and positioned to select a

particular band of frequencies in the selected lasing lobe component. The remainder of the imaging mirror 430 is non-reflective in order that only light in the selected band of frequencies is returned to the laser 428.

It should be noted that Fig. 39 is divided into two parts circumscribed by dotted line boxes. The portion of the figure surrounded by box 434 represents the system as it appears in the slow axis plane (in the plane of the paper), whereas the portion of the system contained within box 436 illustrates the system in the fast axis plane.

In the Fig. 39 embodiment the reflective stripe comprises a portion of a concave mirror. The grating 426 is placed closer to the spatial filter 438 than to the imaging mirror 430 in order that the out-of-plane beam (that is, the beam in the fast-axis plane) fills the grating aperture as completely as possible. Wavelength selection is accomplished by translating the reflective stripe 432 in its own plane, as shown by the arrow in Fig. 39 adjacent the stripe 432.

An embodiment illustrated in Fig. 40 is a variant of the Fig. 39 embodiment wherein the concave reflective stripe 432 in Fig. 39 is replaced by a converging lens 442 and a planar striped mirror 444. The mirror 444 is illustrated as being overlaid by a saturable absorber 443 to provide pulse shaping.

Converging lens 442 is positioned such that it forms a wavelength-selected and inverted real image of the spatial filter in the same plane as the spatial filter, symmetrically disposed below the array axis 446. In the Fig. 40 embodiment, the optical axis of the converging lens 442 and stripe mirror 444 is parallel to the array axis 446 in both the in-plane (slow axis plane) and out-of-plane (fast axis plane) views.

In the Figs. 39 and 40 embodiments, in accordance with the present invention, wavelength dispersion is produced in the fast axis plane, that is, in a plane orthogonal to the plane of mode selection.

The desired band of wavelengths is selected by moving the stripe mirror 444 laterally, that is perpendicular to the axis 445. A small movement of the stripe mirror 444 in the axial direction (along the axis 445) is useful to minimize hopping of the selected longitudinal mode. The axial movement of the stripe mirror 444 should be such that the number of wavelengths in the cavity remains constant while the wavelength is tuned. The lateral and axial movement of the stripe mirror 444 may be coupled so that hopping-free wavelength tuning can be achieved with a coordinated adjusting movement of the stripe mirror 444. A pulse shaping means 443 which may for example be a saturable absorber is located adjacent the stripe mirror 444.

Fig. 41 illustrates an embodiment of the invention similar to the Fig. 40 embodiment but substituting a Littrow grating for the converging lens 442, stripe mirror 444 and grating 448. As is well known, the diffracted rays from a Littrow grating return in the same direction as the incident rays. Wavelength selection is achieved by changing the angle of the grating. The Fig. 41 geometry employs astigmatism compensation by the utilization of an anamorphic lens 452 as in the Fig. 39 embodiment. Also, as in Fig. 39 embodiment, a second converging lens 454 collimates the diverging beam from the waist at the spatial filter 456. The beam is thus collimated at the grating 450 for maximum frequency dispersion by the grating 450.

To minimize wavelength hopping, an axial movement of the grating also may be coupled to an angular movement of the grating. A pulse shaping means 457, which may be a saturable absorber, is located in spatial frequency space in the knife-edge aperture.

Fig. 42 illustrates embodiment of the invention similar to the Fig. 34a embodiment and other embodiments above described, with the exception that an assemblage 460 of multimode micro lasers is substituted

for the single multi-mode micro laser shown in the earlier described embodiments.

It should be understood that in each of the embodiments illustrated and described in this application, a one-dimensional or two dimensional assemblage of multi-mode micro lasers may be employed.

In the Fig. 41 embodiment, with an assemblage of broad area micro lasers, the geometry selects higher order transverse mode lobes in all the uncoupled emitters with the same mode order number. As an example, if the lobe corresponding to the 15th order mode is selected in any of the broad area micro lasers, the same 15th order mode is selected in all of the other lasers.

Whereas a single output beam 462 is shown in the Fig. 42 embodiment, the spatial filter 464 may have a partially reflective coating and produce multiple outputs as shown and described in connection with the embodiments of Figs. 34-40, for example.

Fig. 43 illustrates an embodiment similar to that shown in Fig. 42, except that it is astigmatism corrected by the addition of a cylindrical lens 468. Since coherence across the assemblage 470 of broad area micro lasers in the slow axis plane determines the waist size (spot size) at the knife-edge of the spatial filter 472, the focal length of the cylinder lens 468 is chosen to approximately correct for the ellipticity of the beam. In other words, if incoherence of the emission from the output of the assemblage 470 of broad area micro lasers is such as to create a broadened waist in the beam formed at the spatial filter 472, compared to the near-diffraction limited spot that would be created if the output across the assemblage were coherent, then the cylinder lens 468 will have a convergence in the fast axis plane which is of less power than would be the case if employed with a laser array having a coherent output. The objective is to create an output beam spot as nearly circular as possible, independent of its size. Pulse shaping means 473, which may take the form of active mode locking by

means of acousto-optic modulator, passive mode locking by means of a saturable absorber, or Q-switching by means of an appropriate Q-switch, is located in spatial frequency space in the path of the selected lasing lobe component(s).

Fig. 44 illustrates an embodiment similar to the embodiment shown in Fig. 43, but in which the spatial filter 476 achieves spatial filtering without obstructing the optical axis of the system. This geometry frees the spatial frequency space at which the output beam is converged to a point for introduction to a optical fiber or other optical system or subsystem adapted to receive a relatively high power point source of laser light.

The Fig. 44 embodiment shows the output beam supplied to an angle polished optical fiber 478. In the Fig. 44 embodiment the spatial filter 476 serves no optical coupling or beam take-out function. The Fig. 44 embodiment is thus characterized by the separation of the spatial filtering and beam take-out functions.

Fig. 44a is a schematic perspective view of an embodiment of the invention which is similar to earlier-described embodiments such as the embodiments of Figs. 34a-34b, comprising multi-mode micro laser means 528, a converging lens 530, a spatial filter 532 and an imaging mirror 534. Unlike the Figs. 34a-34b embodiment, the Fig. 44a embodiment includes a two-dimensional assemblage of broad area micro lasers 536. In order to collimate the light emission in the fast axis from each broad area micro laser 536, an elemental anamorphic lens 538 is respectively associated with each laser 536.

The effect of the elemental anamorphic lenses 538 collimating the light from each of the lasers 536 is to produce a collimated beam emanating from the two dimensional assemblage.

The Fig. 44a arrangement is superior to the use of a single anamorphic lens embracing the entire two dimensional assemblage of lasers because the discontinuity of the lasers 536 in the vertical direction (in Fig.

44a) is somewhat compensated (filled up) by the lens array. Hence the fine structure of the image of the waist in the vertical direction will be nearly eliminated by the use of the two-dimensional assemblage of elemental anamorphic lenses 538. The converging lens 530 and the elemental lenses 538 collectively form overlapping images in the fast axis plane of the laser emission aperture at the spatial filter.

The output beam 540 may be coupled into a single mode or multimode fiber placed at the waist 533 formed in the spatial filtering plane.

Figs. 45-48 depict additional embodiments of the invention having a different geometry than the embodiments described above. The Figs. 45-48 embodiments illustrate external cavity laser apparatus comprising multimode micro laser means having an emission aperture with a relatively long dimension lying in a slow axis plane and a relatively short dimension lying in a fast axis plane. The laser means produces multiple transverse lasing modes in the slow axis plane, the multiple transverse modes having multiple lasing lobe components.

An external cavity includes reflecting means which defines one external cavity boundary. First means are provided for effectively isolating at least one selected lasing lobe component in the slow axis plane and for forming with the selected lasing lobe component an image of the emission aperture at the reflecting means. The reflecting means returns the selected lasing lobe component to the first means for reimaging of the emission aperture image into the laser means by the first means.

Fig. 45 depicts external cavity laser apparatus comprising a multimode micro laser 482 having an emission aperture 484. An external mirror 486 has a reflecting surface which constitutes one external cavity boundary.

An imaging mirror 488 is truncated to define a knife-edge 490 serving as a spatial filter for effectively isolating at least one selected lasing

lobe component in the slow axis plane. The imaging mirror 488 forms an image of the emission aperture 484 upon the external mirror 486. The external mirror, here shown as having a planar geometry, returns the selected lasing lobe component to the imaging mirror 488 for reimaging of the emission aperture image into the laser 482 by the imaging mirror 488.

In the Fig. 45 embodiment, no optical elements are provided between the emission aperture 484 of the laser 482 and the spatial filter 490. Transverse modes are spatially filtered by the knife edge 490 on the imaging mirror 488.

Reiterating, the knife edge 490 is located in a spatial frequency plane which is created without the need for imaging lenses as depicted in each of the afore-described embodiments. The imaging mirror 488 is thus placed in the far-field regime of the laser 482. For a laser 482 having an emission aperture 484 with a long dimension of 100 microns, the imaging mirror 488 is placed at least 1.2 centimeters away from the laser 482.

In order to minimize spherical aberration, the imaging mirror may be spherical in configuration and may be located two focal lengths away from each of the laser 482 and the external mirror 486 (that is, at the center of curvature of the mirror 486)

Selection of a desired transverse mode or modes is accomplished by appropriate positioning of the knife-edge 490 of the imaging mirror 488. The positioning and roughness of the knife edge 490 is not as critical as in the above described geometries because lobe widths are greater than the transverse dimension of the array (typically more than 100 microns).

In the Fig. 45 embodiment, the selected lasing lobe is shown schematically by the elongated light pattern 492 formed on the imaging mirror. A representation of the output lasing lobe component is depicted by the elongated figure 494.

Fig. 46 illustrates an embodiment of the invention similar to the embodiment illustrated in Fig. 45, but compensated for astigmatism. In the

Fig. 46 embodiment, an anamorphic lens means is provided, here shown schematically as a cylinder lens 498, for collimating light emanating from the emission aperture 500 of the laser 502 in the fast axis plane. The focal length and position of the cylinder lens 498 are such that the fast axis divergence is equal to the slow axis divergence of the lasing lobe, and beam ellipticity is thereby minimized. The result is an approximately circular selected lasing lobe 504 and an approximately circular output lasing lobe component 506.

In the Fig. 46 embodiment, the imaging mirror 508 and the external mirror 510 are as described with respect to the Fig. 45 embodiment.

Fig. 47 depicts an embodiment of the invention similar to the embodiment shown in Fig. 46, except that beam pulse shaping is provided by a saturable absorber 514 located at the position of the external mirror 516.

The saturable absorber 514 may have a construction and the function as described above with respect to the embodiments illustrated in Fig. 36, for example.

Fig. 48 is another embodiment of the invention which is similar to the Fig. 35 embodiment, but having the capability of lightwave frequency selection. Whereas the Fig. 48 embodiment may employ a planar grating as described above with respect to the embodiments shown in Figs. 39-41, for example, in the preferred Fig. 48 embodiment, frequency dispersion is provided by substituting a concave grating mirror 520 for the imaging mirror shown in Fig. 35.

In order to select a predetermined band of lightwave frequencies in the selected lasing lobe component, the external mirror in the Fig. 48 geometry takes the form of a wavelength selective stripe mirror 522. The stripe mirror 522 is positioned and sized to reflect only a selected band of frequencies of the selected lasing lobe component 524.

In other respects, the Fig. 48 embodiment is similar to the afore-described Fig. 45 embodiment.

Fig. 49 illustrates an alternative to the Fig. 47 embodiment wherein the imaging mirror-spatial filter is replaced by a bulk lens and a separate spatial filter.

Specifically, the Fig. 49 embodiment comprises a multimode micro laser 544 and an external cavity 543. The cavity 543 includes an astigmatism correcting anamorphic lens 545, a converging lens 546 located in the far-field of the laser emission aperture, and a planar reflector 548 upon which an image of the laser emission aperture 547 is formed. A spatial filter 550 is located in spatial frequency space adjacent the lens 546. The spatial filter 550 is shown as being located adjacent the front side of the lens 546, but could alternatively be positioned adjacent the back side of the lens 546. Pulse-shape means 552 is located in front of the reflector 548, but could be located elsewhere in the path of the selected lasing lobe component.

Modifications and alternative embodiments of the invention will be apparent to those skilled in art in view of the foregoing description. This description is to be construed as illustrative only, and is for the purpose of teaching those skilled in the art the best modes for carrying out the invention.

By way of example, it should be understood that features detailed with respect to one or more of the above-described may be employed in other embodiments in which that particular feature may not have been discussed. For example, any of the afore-described embodiments may be provided with pulse shaping, as by the use of a saturable absorber, or with frequency selection capability by the use of a plane or imaging grating combined with a stripe mirror or other frequency selection means.

Also, in all the embodiments above, one can replace the external mirror with a phase conjugating mirror for improved spatial coherence of

the output laser beam, and for reducing the effects of any refractive index inhomogeneity and optical path length variations that may be present in the active region of 1-dimensional and 2-dimensional broad area micro laser emitters. Such inhomogeneity can be present in the optical paths in a micro laser due to temperature variations or due to defects in the crystal lattice of the micro laser. A phase conjugating mirror can be a crystal with nonlinear optical properties polished at a predetermined crystal plane, AR coated and placed at the waist of the beam at a predetermined orientation to serve as a phase conjugating mirror.

The use of converging lens adjacent the emission aperture of the broad area micro laser may not be necessary, as made clear in connection with the description of the Figs. 45-49 embodiments. The use of a converging lens merely moves the far-field closer to the array. In embodiments where compactness is not critical, it may be desirable to accomplish spatial filtering in the farfield created by free space propagation of the transverse modes.

The imaging elements illustrated, whether refractive or reflective, may be provided with correction of spherical aberration or other aberrations. The spatial filtering may be accomplished by means of reflection or transmission, and single or multiple outputs may be provided using the techniques revealed in the embodiments described. An assemblage of broad area micro lasers may be employed with any of the afore-described embodiments, such assemblage being either a one-dimensional assemblage, or a two dimensional stacked assemblage.

The details of the structure and method may thus be varied simultaneously without departing from the spirit of the invention, and the exclusive use of all modifications which come within the scope of the appended claims is reserved.

CLAIMS

1. External cavity micro laser apparatus, comprising:

at least one multimode micro laser means having an emission aperture with a relatively long dimension lying in a slow axis plane and a relatively short dimension lying in a fast axis plane, said laser means producing multiple transverse lasing modes, said multiple modes having multiple lasing lobe components; and

external cavity means embracing said laser means and comprising:

an output section having an output beam, said output section including:

spatial filter means for effectively selecting at least one of said transverse lasing lobe components;

imaging means for imaging at said spatial filter means a far field spatial frequency distribution of said emission aperture in the slow axis plane, at which said lasing lobe components are spatially distinguishable; and

feedback means distinct from and located beyond said spatial filter means for causing a fraction of the optical energy in said selected lasing lobe components to be fed back to said laser means for amplification by said laser means; and

a return section receiving said amplified lasing lobe component after reflection from said laser means, said return section including return means for efficiently returning to said laser means at least a portion of said amplified and reflected lasing lobe component.

2. The apparatus defined by claim 1 which includes optical waveguide means having cladding and a core with an input aperture, and wherein said input aperture constitutes said spatial filter means.

3. The apparatus defined by claim 2 including mode scrambling means located in advance of said input aperture for mixing the spatial modes of the waveguide means

4. The apparatus defined by claim 2 wherein said feedback means comprises partially reflective means disposed beyond said input aperture .

5. The apparatus defined by claim 4 wherein said input aperture is sized and positioned to select a predetermined plurality of said transverse modes and said modes are mixed within said optical waveguide before being fed back to said laser means by said partially reflective means in order to improve the spatial coherence of the optical energy in said output section.

6. The apparatus defined by claim 4 wherein said partial reflecting means comprises a cut and polished terminal surface on said waveguide means.

7. The apparatus defined by claim 4 wherein said partial reflecting means comprises a Bragg grating in the core of the said waveguide means.

8. The apparatus defined by claim 7 wherein said Bragg grating in the core has a width smaller than the width of the core of the said waveguide means.

9. The apparatus defined by claim 4 wherein said partial reflecting means comprises a frequency-dispersive grating and a reflector for reflecting laser energy received from said grating back to said grating for return to said laser means.

10. The apparatus defined by claim 4 wherein said waveguide means is looped back upon itself to form a Sagnac reflector loop serving as said partial reflecting means.

11. The apparatus defined by claim 10 wherein said apparatus includes a polarization controller located in the region of said loop for controlling said predetermined fraction of laser energy returned to said laser means and its plane of polarization.

12. The apparatus defined by claim 4 wherein said partial reflecting means is wavelength selective and comprises a directional waveguide coupler on said waveguide means followed in said waveguide means by wavelength-selective grating means which returns light in a selected band of frequencies back to said laser means.

13. The apparatus defined by claim 4 wherein said partial reflecting means comprises pulse-shaping means located in said laser energy, said pulse-shaping means reflecting said predetermined fraction of laser energy from a back surface thereof.

14. The apparatus defined by claim 4 wherein said partial reflecting means is wavelength selective and comprises a fiber coupler on said waveguide means followed in said waveguide means by pulse-shaping means and mirror means which returns pulse-shaped laser energy to said laser means.

15. The apparatus defined by claim 1 wherein said output beam cross-section distribution has a high aspect ratio and said input aperture is more circularly symmetric, and wherein said imaging means has an anamorphic component for reshaping said output beam to better conform to said input aperture.

16. The apparatus defined by claim 15 wherein said anamorphic component is effective at least in said output section.

17. The apparatus defined by claim 15 wherein said anamorphic component is effective in both said output section and said return section of said external cavity.

18. The apparatus defined by claim 15 wherein said anamorphic component is effective only in said output section of said external cavity.

19. The apparatus defined by claim 15 including crossed cylindrical lens means of different power.

20. The apparatus defined by claim 1 wherein said return section of said external cavity includes mirror means.

21. The apparatus defined by claim 20 which includes optical waveguide means having cladding and a core with an input aperture, wherein said input aperture constitutes said spatial filter means, and wherein said mirror means is contiguous to said input aperture.

22. The apparatus defined by claim 21 wherein said waveguide means includes said mirror mean.

23. The apparatus defined by claim 21 including a ferrule which captures said waveguide means, and wherein a portion of an end surface of said ferrule spaced from said input aperture defines said mirror means.

24. The apparatus defined by claim 20 wherein said mirror means is planar.

25. The apparatus defined by claim 20 wherein said mirror means has imaging properties.

26. The apparatus defined by claim 20 wherein said mirror means is a phase conjugating mirror.

27. The apparatus defined by claim 1 wherein said apparatus includes means for frequency dispersing the optical energy in said external cavity and for selecting a predetermined band of lightwave frequencies in the dispersed optical energy.

28. The apparatus defined by claim 1 wherein said apparatus includes pulse shaping means located in said external cavity.

29. External cavity micro laser apparatus, comprising:

multimode micro laser means having an emission aperture and producing an output beam having a fundamental mode and multiple transverse lasing modes having a plurality of lasing lobe components; and

optical waveguide means having an input aperture;

imaging means receiving said output beam and imaging at said input aperture a far field spatial frequency distribution of said emission aperture in the slow axis plane, at which distribution said lasing lobe components are spatially distinguishable, said input aperture being sized and positioned to select one or more predetermined lasing lobe components; and

partial reflecting means after said input aperture for returning a predetermined fraction of the optical energy in said waveguide means to said laser means,

selected lasing lobe components mixing in said waveguide between said input aperture and said partial reflecting means such that the coherence of the output beam is thereby improved.

30. The apparatus defined by claim 29 wherein said laser means comprises a two-dimensional matrix of emitters.

31. The apparatus defined by claim 29 wherein said output beam cross-section has a high aspect ratio and said input aperture is more circularly symmetric, and wherein said imaging means has an anamorphic component for reshaping said output beam to better conform to said input aperture.

32. Micro laser apparatus, comprising:

multimode micro laser means having an emission aperture and producing an output beam having a fundamental mode and multiple transverse lasing modes having a plurality of lasing lobe components;

optical waveguide means having an input aperture; and

imaging means for imaging at said input aperture a far field spatial frequency distribution of said emission aperture in a slow axis plane of the laser means, at which distribution said lasing lobe components are spatially distinguishable, said input aperture being sized and positioned to select one or more predetermined lasing lobe components.

33. The apparatus defined by claim 32 wherein said optical waveguide means has a cladding and has a core with said input aperture, said input aperture receiving an output laser beam from said laser means and having laterally spaced therefrom mirror means for returning back to said laser means laser energy which has been reflected from said laser means.

34. The apparatus defined by claim 32 wherein said output beam cross-section has a high aspect ratio and said input aperture is more circularly symmetric, and wherein said imaging means has an anamorphic component for reshaping said output beam to better conform to said input aperture.

35. The apparatus defined by claim 34 wherein said imaging means comprises an anamorphic lens and a non-anamorphic lens.

36. The apparatus defined by claim 34 wherein said imaging means comprises crossed anamorphic lenses.

37. The apparatus defined by claim 36 wherein said imaging means comprises crossed cylinder lenses.

38. The apparatus defined by claim 32 wherein said waveguide means is sized and positioned such that said input aperture selects said fundamental lasing lobe component.

39. The apparatus defined by claim 32 wherein said waveguide means is sized and positioned to select a plurality of said transverse lasing lobe components.

40. The apparatus defined by claim 32 wherein said laser means comprises a two-dimensional matrix of emitters.

41. The apparatus defined by claim 32 wherein said partial reflecting means comprises a cut and polished terminal surface on said waveguide means.

42. The apparatus defined by claim 32 wherein said partial reflecting means comprises a Bragg grating in said waveguide means.

43. The apparatus defined by claim 42 wherein said Bragg grating in the core has a width smaller than the width of the core of the said waveguide means.

44. The apparatus defined by claim 32 wherein said partial reflecting means comprises a frequency-dispersive grating and a reflector for reflecting laser energy received from said grating back to said grating for return to said laser means.

45. The apparatus defined by claim 32 wherein said waveguide means is looped back upon itself to form a Sagnac reflector loop serving as said partial reflecting means.

46. The apparatus defined by claim 45 wherein said apparatus includes a polarization controller located in the region of said loop for controlling said predetermined fraction of laser energy returned to said laser means and its plane of polarization.

47. The apparatus defined by claim 32 wherein said partial reflecting means is wavelength selective and comprises a directional waveguide coupler on said waveguide means followed in said waveguide means by wavelength-selective grating means which returns light in a selected band of frequencies back to said laser means.

48. The apparatus defined by claim 32 wherein said partial reflecting means comprises pulse-shaping means located in said laser energy, said pulse-shaping means reflecting said predetermined fraction of laser energy from a back surface thereof.

49. The apparatus defined by claim 32 wherein said partial reflecting means is wavelength selective and comprises a fiber coupler on said waveguide means followed in said waveguide means by pulse-shaping means and mirror means which returns pulse-shaped laser energy to said laser means.

50. The apparatus defined by claim 32 including mode scrambling means located in advance of said input aperture for mixing the spatial modes of said waveguide means.

51. External cavity micro laser apparatus, comprising:

multimode micro laser means producing output laser energy;

an external cavity including said laser means and having first and second reflective means defining the boundaries of the cavity;

optical waveguide means having an input aperture;

imaging means for converging said output laser energy into said input aperture of said waveguide means; and

partial reflecting means located beyond said input aperture and constituting said second reflective means for returning a predetermined fraction of the optical energy in said waveguide means to said laser means.

52. The apparatus defined by claim 51 wherein said laser means comprises a two-dimensional matrix of emitters.

53. The apparatus defined by claim 51 wherein said laser means comprises a one-dimensional array of emitters.

54. The apparatus defined by claim 51 wherein said reflective means is a phase conjugate mirror.

55. The apparatus defined by claim 51 wherein said partial reflecting means comprises a cut and polished terminal surface on said waveguide means.

56. The apparatus defined by claim 51 wherein said partial reflecting means comprises a Bragg grating in said waveguide means.

57. The apparatus defined by claim 51 wherein said partial reflecting means comprises a frequency-dispersive grating and a reflector for reflecting laser energy received from said grating back to said grating for return to said laser means.

58. The apparatus defined by claim 51 wherein said waveguide means is looped back upon itself to form a Sagnac reflector loop serving as said partial reflecting means.

59. The apparatus defined by claim 58 wherein said apparatus includes a polarization controller located in the region of said loop for controlling said predetermined fraction of laser energy returned to said laser means and its plane of polarization.

60. The apparatus defined by claim 51 wherein said partial reflecting means is wavelength selective and comprises a directional waveguide coupler coupled into said waveguide means followed in said waveguide means by wavelength-selective grating means which returns light in a selected band of frequencies back to said laser means.

61. The apparatus defined by claim 51 wherein said partial reflecting means comprises pulse-shaping means located in said laser energy, said pulse-shaping means reflecting said predetermined fraction of laser energy from a back surface thereof.

62. The apparatus defined by claim 51 wherein said partial reflecting means is wavelength selective and comprises a fiber coupler on said waveguide means followed in said waveguide means by pulse-shaping means and mirror means which returns pulse-shaped laser energy to said laser means.

63. The apparatus defined by claim 51 including mode scrambling means located in advance of said input aperture for mixing the spatial modes of the waveguide means.

64. For use with external cavity laser apparatus including multimode micro laser means for generating an output laser beam, optical waveguide means having cladding and a core and having waveguide input means comprising a core input aperture for receiving said output laser beam and having laterally spaced therefrom mirror means for returning back to said laser means laser energy which has been reflected from said laser means.

65. The apparatus defined by claim 64 wherein an input termination of said optical waveguide means is captured in a ferrule which has a dual facet chisel-shaped termination with said core input aperture being located in one facet slightly offset from an edge formed at the convergence of said facets.

66. The apparatus defined by claim 65 wherein said one facet has a slope angle substantially equal to the Brewster angle.

67. The apparatus defined by claim 66 including means for utilizing light reflected off said one facet to monitor the location or other parameter of the output beam.

68. The apparatus defined by claim 65 wherein a wedge is positioned on the other of said dual facets and has a reflective surface constituting said mirror means.

69. The apparatus defined by claim 68 wherein the mirror means is a phase conjugating mirror.

70. The apparatus defined by claim 64 wherein said optical waveguide means has at its termination a facet sloping away from said laser means, said core input aperture being located in said sloping facet.

71. The apparatus defined by claim 70 wherein said facet has a slope angle substantially equal to the Brewster angle.

72. The apparatus defined by claim 70 including means for utilizing light reflected off said facet to monitor the location or other parameter of the output beam.

73. The apparatus defined by claim 64 wherein an end portion of said waveguide means is captured in a ferrule, and wherein a portion of an end surface of said ferrule spaced from said core input aperture defines said mirror means.

74. The apparatus defined by claim 64 wherein said mirror means comprises a discrete reflector contiguous to said fiber.

75. The apparatus defined by claim 64 wherein said waveguide input means includes mode scrambling means located in advance of said input aperture for mixing the spatial modes of the waveguide means.

76. Micro laser apparatus, comprising:

micro laser array means comprising a spaced plurality of laser emitters, said emitters emitting a like plurality of laterally spaced parallel beamlets; and

despacing means optically coupled to said laser array means for reducing the spacing between said beamlets while preserving their parallelism to form a more concentrated output beam.

77. The apparatus defined by claim 76 wherein said emitters are of number N and are arranged in a linear array, and wherein said despacing means comprises means for deflecting at least N minus one of said beamlets into a state of contiguous parallelism.

78. The apparatus defined by claim 76 wherein said emitters are of number N and wherein said despacing means comprises a parallel stack of beamlet translation elements of number at least equal to N minus one respectively associated with said beamlets, each of said beamlet-translation elements being arranged at a common angle with respect to its respectively associated beamlet, said beamlet-translation elements being constructed and arranged to offset said beamlets into a state of contiguous parallelism.

79. The apparatus defined by claim 78 wherein said common angle is substantially equal to the Brewster angle.

80. The apparatus defined by claim 78 wherein each of said beamlet-translation elements comprises a glass slide having a beveled front face effective to prevent interference with an adjacent beamlet.

81. The apparatus defined by claim 76 wherein said emitters are arranged in a linear array along a slow axis of the laser array, and wherein said apparatus includes anamorphic lens means having less refractive power in the direction of said slow axis than in the direction of a fast axis orthogonal to said slow axis.

82. The apparatus defined by claim 76 wherein said emitters are arranged in a linear array along a slow axis of the laser array, wherein said emitters are of a number N, and wherein said despacing means comprises at least N minus one prisms respectively associated with said emitters, said prisms being constructed and arranged to redirect the respectively associated beamlets into a state of contiguous parallelism.

83. The apparatus defined by claim 76 wherein said emitters are of number N and wherein said despacing means comprises an array of beamlet-translation elements of number at least equal to N minus one respectively associated with said beamlets, said beamlet-translation elements being constructed and arranged to offset said beamlets into a state of contiguous parallelism.

84. The apparatus defined by claim 83 wherein said beamlet-translation elements are divided into two groups having a mirror image relationship with respect to each other such that a resulting merged output beam is substantially centered relative to said laser array means.

85. External cavity micro laser apparatus, comprising:

multi-mode micro laser means producing multiple transverse lasing modes, said multiple transverse modes having multiple lasing lobe components; and

external cavity means, comprising:

spatial filter means for effectively isolating at least one selected lasing lobe component; and

imaging and reflecting means constructed and arranged to receive said selected lasing lobe component isolated by said spatial filter means and to reimage at said spatial filter means said selected lasing lobe component.

86. The apparatus defined by claim by 85 including pulse shaping means.

87. The apparatus defined by claim by 86 wherein said pulse shaping means comprises a saturable absorber.

88. The apparatus defined by claim by 86 wherein said imaging and reflecting means comprise discrete imaging means and reflecting means, and wherein said pulse shaping means is located at said reflecting means.

89. The apparatus defined by claim by 88 wherein said pulse shaping means comprises a saturable absorber.

90. The apparatus defined by claim 85 wherein said reflecting means is a phase conjugate mirror.

91. The apparatus defined by claim by 85 wherein said apparatus includes lightwave frequency selecting means.

92. The apparatus defined by claim by 91 wherein said apparatus includes frequency dispersive means, wherein said imaging and reflecting means comprises integrated imaging means and reflecting means having a reflective element sized and positioned to receive said selected lasing lobe component reflected from said frequency dispersive means and to select a predetermined band of lightwave frequencies in said selected lasing lobe component.

93. The apparatus defined by claim 92 wherein said frequency dispersive means comprises a grating positioned between said laser means and said reflective element.

94. The apparatus defined by claim by 85 wherein said imaging and reflecting means comprises discrete imaging means and reflecting means, and wherein said reflecting means includes a frequency dispersive grating.

95. The apparatus defined by claim by 94 wherein said grating comprises a Littrow grating.

96. The apparatus defined by claim by 85 wherein said imaging and reflecting means comprises frequency-dispersive imaging mirror means.

97. The apparatus defined by claim 85 wherein said laser means comprises an array of semiconductor broad area micro lasers.

98. The apparatus defined by claim 85 wherein said laser means comprises a two-dimensional matrix of broad area micro lasers.

99. The apparatus defined by claim 85 wherein said laser means comprises an area emitter.

100. The apparatus defined by claim 85 including means for providing multiple output beams.

101. External cavity micro laser apparatus, comprising:

multi-mode micro laser means having an emission aperture with a relatively long dimension lying in a slow axis plane and a relatively short dimension lying in a fast axis plane, said laser means producing multiple transverse lasing modes in said slow axis plane, said multiple transverse modes having multiple lasing lobe components; and

external cavity means, comprising:

first imaging means for converting an object plane at said emission aperture into a spatial frequency distribution located at a predetermined spatial frequency plane;

spatial filter means located at said spatial frequency plane for effectively isolating at least one selected lasing lobe component in said slow-axis plane; and

imaging and reflecting means constructed and arranged to receive said selected lasing lobe component isolated by said spatial filter means at said spatial frequency plane and to form a reimage in said slow axis plane and at said spatial filter means of said selected lasing lobe component for return to said laser means.

102. The apparatus defined by claim 101 wherein said reflecting means comprises a phase conjugate mirror.

103. The apparatus defined by claim 101 wherein said imaging and reflecting means comprises imaging mirror means.

104. The apparatus defined by claim 103 wherein said imaging mirror means comprises a grating mirror.

105. The apparatus defined by claim by 101 including pulse shaping means.

106. The apparatus defined by claim 105 wherein said pulse shaping means comprises a saturable absorber.

107. The apparatus defined by claim 101 including anamorphic imaging means cooperating with said first imaging means to form a point image of said reimage in space after reflection of said lasing lobe component from said laser means.

108. The apparatus defined by 101 wherein said imaging and reflecting means comprises discrete imaging means and reflecting means, and wherein in said fast axis plane said first imaging means forms an image of said emission aperture of said laser means at said reflecting means.

109. The apparatus defined by claim 108 wherein said reflecting means is a phase conjugate mirror.

110. The apparatus defined by claim by 101 including anamorphic imaging means cooperating with said first imaging means such that in said fast axis plane, said first imaging means and said anamorphic imaging means collectively image said emission aperture at said spatial filter means.

111. The apparatus defined by claim by 101 wherein said laser means comprises a two dimensional matrix of elemental broad area micro lasers .

112. The apparatus defined by claim by 111 including an elemental anamorphic lens mans associated with each of said elemental broad area micro lasers, said first imaging means and said elemental anamorphic lens means collectively forming in said fast axis plane at said spatial filter means overlapping images of said emission aperture.

113. The apparatus defined by claim 111 wherein said laser means comprises a two dimensional surface emitter.

114. External cavity micro laser apparatus, comprising:

multi-mode micro laser means having an emission aperture with a relatively long dimension lying in a slow axis plane and a relatively short dimension lying in a fast axis plane, said laser means producing multiple transverse lasing modes in said slow axis plane, said multiple transverse modes having multiple lasing lobe components; and

external cavity means, comprising:

spatial filter means for effectively isolating at least one selected lasing lobe component in said slow-axis plane;

imaging and reflecting means constructed and arranged to receive said selected lasing lobe component isolated by said spatial filter means and to image in said slow axis plane and at said spatial filter means said selected lasing lobe component for return to said laser means; and

take-off means positioned and angled such that the selected lasing lobe component returned to said laser means is redirected out of said apparatus.

115. The apparatus defined by claim 114 wherein said imaging and reflecting means comprises discrete imaging means and reflecting means.

116. The apparatus defined by claim 114 wherein in said reflecting means is a phase conjugate mirror.

117. The apparatus defined by claim 114 wherein said imaging and reflecting means includes imaging mirror means.

118. The apparatus defined by claim 115 wherein said imaging means includes a graded index lens.

119. The apparatus defined by claim 114 wherein said spatial filter means includes knife edge means.

120. The apparatus defined by claim 119 wherein said knife edge means comprises an angled reflector and doubly functions as said take-off means.

121. The apparatus defined by claim by 119 wherein said knife edge means is composed of a light transmissive medium, and wherein said knife edge means has an angled surface which is partially light reflective and partially light transmissive, said knife edge means producing separated outputs.

122. The apparatus defined by claim by 119 wherein said knife edge means is composed of a light transmissive medium, and wherein said knife edge means has an angled surface constituting said take-off means and produces a refracted output.

123. The apparatus defined by claim by 114 wherein said laser means comprises a two-dimensional matrix of elemental broad area micro lasers.

124. The apparatus defined by claim 114 wherein said take-off means provides multiple output beams.

125. The apparatus defined by claim 124 wherein one of said output beams is a main output beams and another is a secondary beam for monitoring said main output beam.

126. External cavity micro laser apparatus, comprising:

multi-mode micro laser means having an emission aperture with a relatively long dimension lying in a slow axis plane and a relatively short dimension lying in a fast axis plane, said laser means producing multiple transverse lasing modes in said slow axis plane, said multiple transverse modes having multiple lasing lobe components; and

external cavity means, comprising:

first imaging means for converting an object plane at said emission aperture into a spatial frequency distribution located at a predetermined spatial frequency plane;

spatial filter means located at said spatial frequency plane for effectively isolating at least one selected lasing lobe component in said slow-axis plane;

imaging and reflecting means constructed and arranged to receive said selected lasing lobe component isolated by said spatial filter means at said spatial frequency plane and to image in said slow axis plane and at said spatial filter means said selected lasing lobe component for return to said laser means; and

take-off means positioned and angled such that the selected lasing lobe component returned to said laser means is redirected out of said apparatus.

127. The apparatus defined by claim 126 wherein said imaging and reflecting means comprises discrete imaging means and reflecting means.

128. The apparatus defined by claim 126 wherein said reflecting means comprises a phase conjugate mirror.

129. The apparatus defined by claim 127 wherein in said fast axis plane, said first imaging means forms an image of said emission aperture of said laser means at said reflecting means.

130. The apparatus defined by claim 126 wherein said spatial filter means includes knife edge means.

131. The apparatus defined by claim by 126 including anamorphic imaging means cooperating with said first imaging means such that in said fast axis plane, said first imaging means and said anamorphic imaging means collectively image said emission aperture at said spatial filter means.

132. The apparatus defined by claim by 126 wherein said laser means comprises a two dimensional matrix of elemental broad area micro lasers.

133. The apparatus defined by claim by 132 including an elemental anamorphic lens mans associated with each of said elemental broad area micro lasers, said first imaging means and said elemental anamorphic lens means collectively imaging said emission aperture at said spatial filter means.

134. External cavity micro laser apparatus, comprising:

multi-mode micro laser means producing multiple transverse lasing modes, said multiple transverse modes having multiple lasing lobe components; and

external cavity means, comprising:

spatial filter means for effectively isolating at least one selected lasing lobe component; and

imaging mirror means constructed and arranged to receive said selected lasing lobe component isolated by said spatial filter means and to image at said spatial filter means said selected lasing lobe component.

135. The apparatus defined by claim 134 wherein said spatial filter means includes knife edge means.

136. The apparatus defined by claim 135 wherein said knife edge means comprises an angled knife edge which passes said selected lasing lobe component and rejects non-selected lasing lobe components.

137. The apparatus defined by claim 134 including take-off means positioned and angled such that the selected lasing lobe component is redirected out of said apparatus.

138. The apparatus defined by claim 137 wherein said spatial filter means comprises an angled knife edge which passes said selected lasing lobe component and rejects non-selected lobe components.

139. The apparatus defined by claim 138 wherein said knife edge means is reflective and doubly serves as said take-off reflector means.

140. The apparatus defined by claim 134 wherein said imaging mirror means is tilted by a predetermined angle effective to image said selected lasing lobe component at said spatial filter means.

141. The apparatus defined by claim 134 wherein said imaging mirror means includes a phase conjugate mirror.

142. The apparatus defined by claim by 134 wherein said imaging mirror means is translated parallel to a system optical axis by a predetermined distance effective to image said selected lasing lobe component at said spatial filter means.

143. The apparatus defined by claim by 134 wherein said imaging mirror means is formed with a grating surface for lightwave frequency dispersion.

144. The apparatus defined by claim by 134 wherein a lightwave frequency dispersive grating is positioned between said imaging mirror means and said spatial filter for lightwave frequency dispersion.

145. The apparatus defined by claim 134 wherein said first imaging means comprises a graded index lens.

146. External cavity micro laser apparatus, comprising:

multi-mode micro laser means having an emission aperture with a relatively long dimension lying in a slow axis plane and a relatively short dimension lying in a fast axis plane, said laser means producing multiple transverse lasing modes in said slow axis plane, said multiple transverse modes having multiple lasing lobe components; and

external cavity means, comprising:

first imaging means for converting an object plane at said emission aperture into a spatial frequency distribution located at a predetermined spatial frequency plane; and

spatial filter means located at said spatial frequency plane for effectively isolating at least one selected lasing lobe component in said slow-axis plane;

imaging mirror means constructed and arranged to receive said selected lasing lobe component isolated by said spatial filter means at said spatial frequency plane and to image in said slow axis plane and at said spatial filter means said selected lasing lobe component for return to said laser means.

147. The apparatus defined by claim 146 wherein in said fast axis plane, said first imaging means forms an image of said emission aperture of said laser means at said mirror means.

148. The apparatus defined by claim 146 wherein the imaging mirror means is a phase conjugate mirror.

149. External cavity micro laser apparatus, comprising:

multi-mode micro laser means producing multiple transverse lasing modes, said multiple transverse modes having multiple lasing lobe components; and

external cavity means, comprising:

spatial filter means positioned and arranged to pass at least one selected lasing lobe component while reflectively rejecting non-selected lobe components; and

imaging and reflecting means constructed and arranged to receive said selected lasing lobe component isolated by said spatial filter means and to image at said spatial filter means said selected lasing lobe component for return to said laser means, certain lasing lobe components being rejected by said spatial filter mans outbound, and due to image inversion by said imaging and reflecting means, other lasing lobe components being rejected inbound, leaving said selected lasing lobe component for amplification by said laser means.

150. The apparatus defined by claim 149 wherein said imaging and reflecting means includes imaging mirror means.

151. The apparatus defined by claim 149 wherein the imaging and reflecting means includes a phase conjugate mirror.

152. The apparatus defined by claim 149 wherein said imaging and reflecting means comprises discrete imaging means and reflecting means.

153. The apparatus defined by claim 152 wherein said imaging means includes a graded index lens.

154. The apparatus defined by claim 149 wherein said spatial filter means includes knife edge means.

155. The apparatus defined by claim 154 wherein said knife edge means comprises an angled reflector.

156. The apparatus defined by claim by 154 wherein said knife edge means is composed of a light transmissive medium, and wherein said knife edge means has an angled surface which is partially light reflective and partially light transmissive, said knife edge means producing separated outputs.

157. The apparatus defined by claim by 154 wherein said knife edge means is comprised of a light transmissive medium, and wherein said knife edge means has an angled surface and produces a refracted output.

158. The apparatus defined by claim by 149 wherein said laser means comprises a two dimensional matrix of elemental broad area micro lasers.

159. External cavity micro laser apparatus, comprising:

multi-mode micro laser means having an emission aperture with a relatively long dimension lying in a slow axis plane and a relatively short dimension lying in a fast axis plane, said laser means producing multiple transverse lasing modes in said slow axis plane, said multiple transverse modes having multiple lasing lobe components; and

external cavity means, comprising:

first imaging means for converting an object plane at said emission aperture into a spatial frequency distribution located at a predetermined spatial frequency plane;

spatial filter means located at said spatial frequency plane for effectively isolating at least one selected lasing lobe component in said slow-axis plane; and

imaging and reflecting means constructed and arranged to receive said selected lasing lobe component isolated by said spatial filter means and to image at said spatial filter means said selected lasing lobe

component for return to said laser means, certain lasing lobe components being rejected by said spatial filter mans outbound, and due to image inversion by said imaging and reflecting means, other lasing lobe components being rejected inbound, leaving said selected lasing lobe component for amplification by said laser means.

160. The apparatus defined by claim 159 wherein in said fast axis plane, said first imaging means forms an image of said emission aperture of said laser means at said reflecting means.

161. The apparatus defined by claim 159 wherein the reflecting means includes a phase conjugate mirror.

162. External cavity micro laser apparatus, comprising:

multi-mode micro laser means having an emission aperture with a relatively long dimension lying in a slow axis plane and a relatively short dimension lying in a fast axis plane, said laser means producing multiple transverse lasing modes in said slow axis plane, said multiple transverse modes having multiple lasing lobe components; and

external cavity means, comprising:

first graded index lens means for converting an object plane at said emission aperture into a spatial frequency distribution located at a predetermined spatial frequency plane;

spatial filter means located at said spatial frequency plane for effectively isolating at least one selected lasing lobe component in said slow-axis plane; and

imaging and reflecting means constructed and arranged to receive said selected lasing lobe component isolated by said spatial filter means at said spatial frequency plane and to image in said slow axis plane and at said spatial filter means said selected lasing lobe component for return to said laser means, said imaging and reflecting means comprising a

second graded index lens means, said second graded index lens means being separate from said first graded index lens means.

163. The apparatus defined by claim 162 wherein said imaging and reflecting means comprises discrete imaging means and reflecting means.

164. The apparatus defined by claim 162 wherein said imaging and reflecting means includes a phase conjugate mirror.

165. The apparatus defined by claim 162 wherein in said fast axis plane, said first lens means forms an image of said emission aperture of said laser means at said reflecting means.

166. The apparatus defined by claim 162 wherein said spatial filter means includes knife edge means.

167. The apparatus defined by claim 162 wherein said knife edge means comprises an angled knife edge which passes said selected lasing lobe component and rejects non-selected lasing lobe components.

168. The apparatus defined by claim 162 including take-off means positioned and angled such that the selected lasing lobe component is redirected out of said apparatus.

169. The apparatus defined by claim 168 wherein said spatial filter means comprises an angled knife edge which passes said selected lasing lobe component and rejects non-selected lobe components.

170. The apparatus defined by claim 169 wherein said knife edge means is reflective and doubly serves as said take-off reflector means.

171. External cavity micro laser apparatus, comprising:

multi-mode micro laser means having an emission aperture with a relatively long dimension lying in a slow axis plane and a relatively short dimension lying in a fast axis plane, said laser means producing multiple transverse lasing modes in said slow axis plane, said multiple transverse modes having multiple lasing lobe components; and

external cavity means, comprising:

reflecting means constituting one external cavity boundary; and

first means for effectively isolating at least one selected lasing lobe component in said slow axis plane and for forming with said selected lasing lobe component an image of said emission aperture at said reflecting means, said reflecting means returning said selected lasing lobe component to said first means for reimaging of said emission aperture image into said laser means by said first means.

172. The apparatus defined by claim 171 wherein said first means includes imaging mirror means.

173. The apparatus defined by claim 172 wherein said imaging mirror means has a knife edge serving as said spatial filter means.

174. The apparatus defined by claim 171 wherein said first means comprises regarding lens means and discrete spatial filter means.

175. The apparatus defined by claim 171 including anamorphic imaging means for collimating light emanating from said emission aperture in said fast axis plane.

176. The apparatus defined by claim 171 including pulse shaping means located at said reflecting means.

177. The apparatus defined by claim 176 wherein said pulse shaping means comprises saturable absorber means.

178. The apparatus defined by claim 171 wherein said apparatus includes frequency dispersive means.

179. The apparatus defined by claim 178 wherein said frequency dispersive means comprises a grating.

180. The apparatus defined by claim 179 wherein said first means comprises a concave grating mirror constituting said frequency dispersive means.

181. The apparatus defined by claim 179 wherein said reflecting means comprises a reflective element positioned and sized to reflect only a selected band of frequencies of said lasing lobe component.

182. External cavity micro laser apparatus, comprising:

multi-mode micro laser means having an emission aperture with a relatively long dimension lying in a slow axis plane and a relatively short dimension lying in a fast axis plane, said laser means producing multiple transverse lasing modes in said slow axis plane, said multiple transverse modes having multiple lasing lobe components; and

external cavity means, comprising:

spatial filter means located in a spatial frequency plane corresponding to said emission aperture plane for effectively isolating at least one selected lasing lobe component in said slow-axis plane; and

frequency selection means including means for frequency dispersing said selected lasing lobe component in said fast axis plane, and means for selecting in said selected lasing lobe component a predetermined band of lightwave frequencies for return to said laser means.

183. The apparatus defined by claim 182 wherein said frequency dispersing means includes a grating.

184. The apparatus defined by claim 182 wherein said means for selecting comprises a reflective stripe positioned and sized in said lasing lobe component to reflectively select only said predetermined band of lightwave frequencies.

185. The apparatus defined by claim 184 wherein said selecting means includes a phase conjugate mirror.

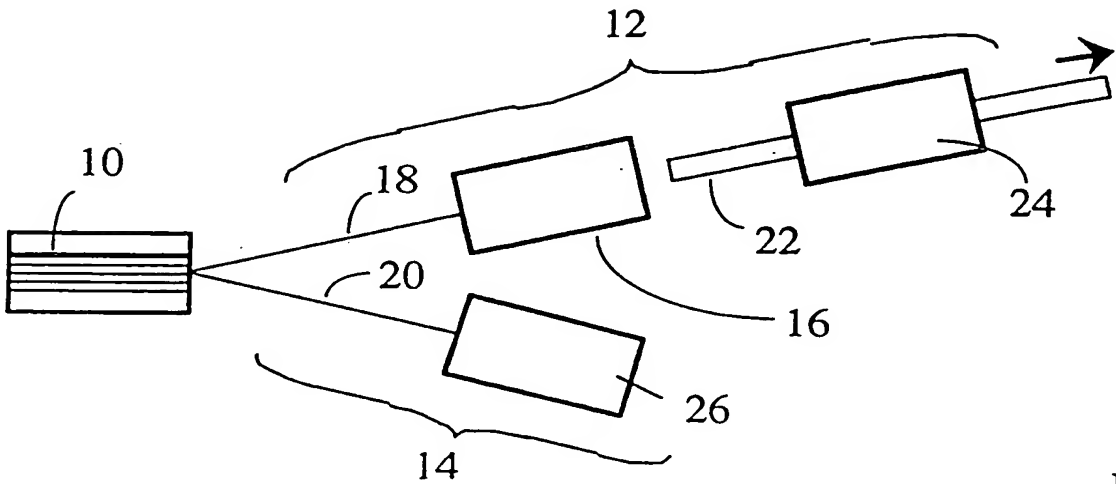

FIG. 1

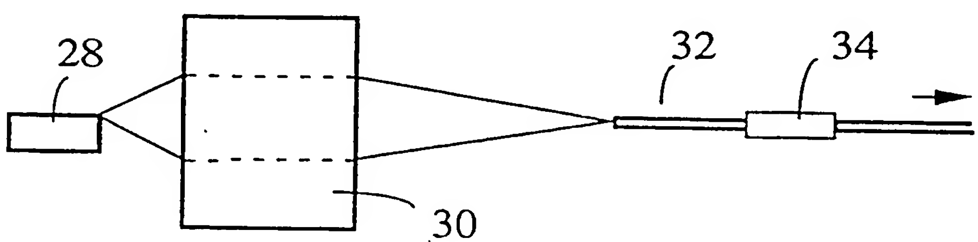

FIG. 2

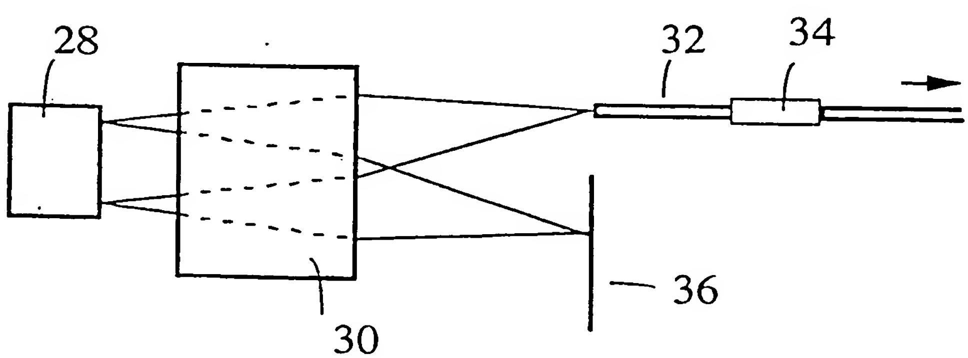

FIG. 3

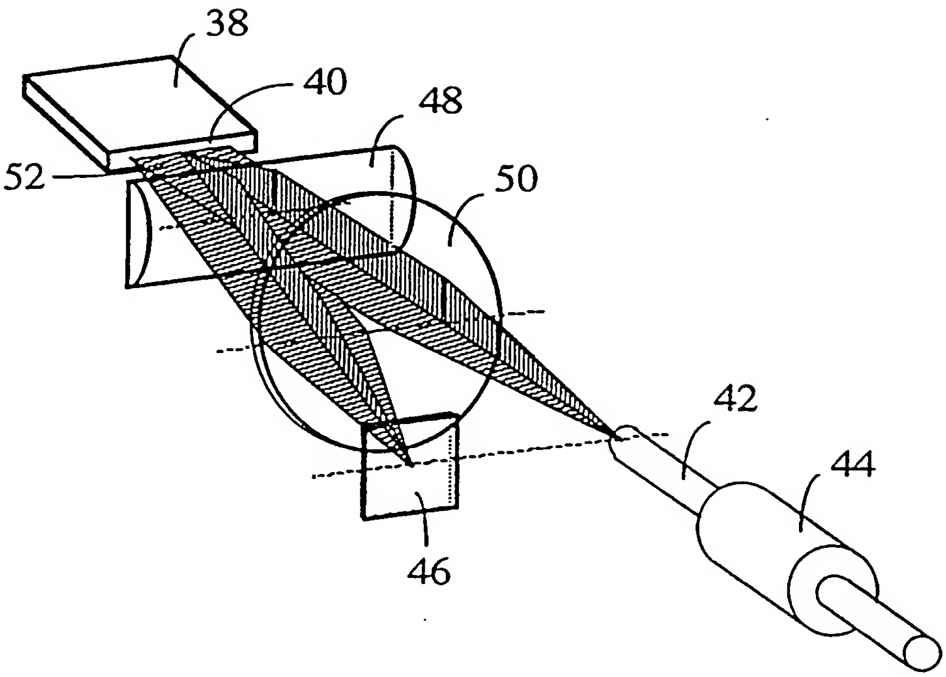

FIG. 4

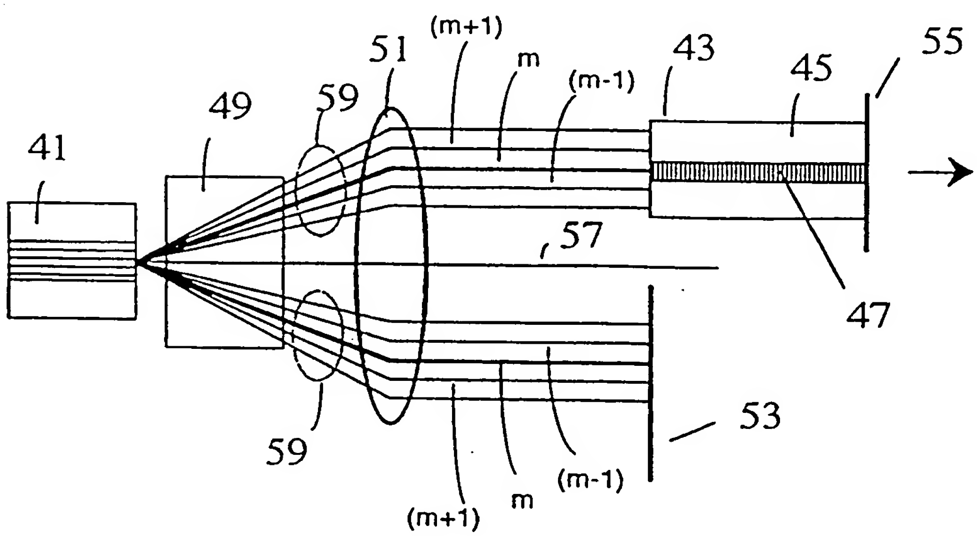

FIG. 4A

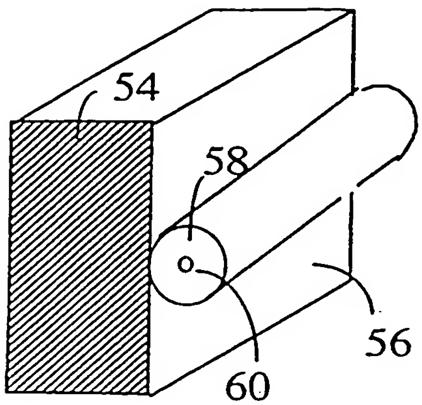

FIG. 5

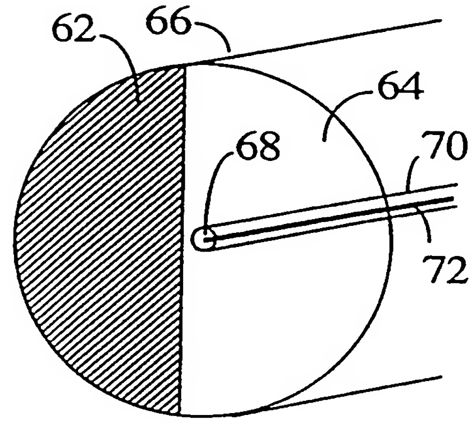

FIG. 6

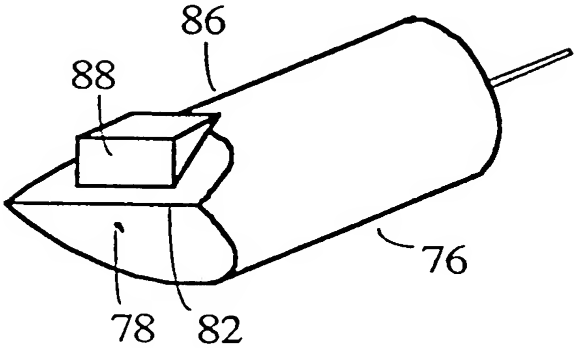

FIG. 7

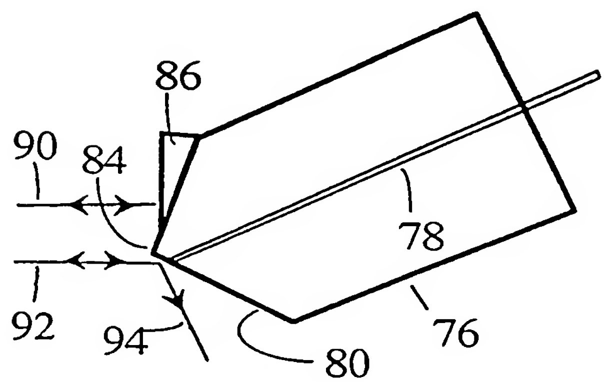

FIG. 8

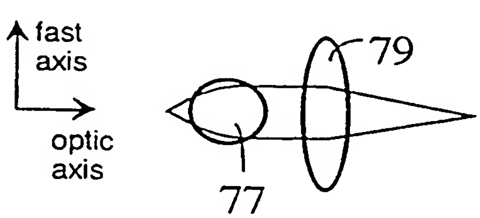

FIG. 9

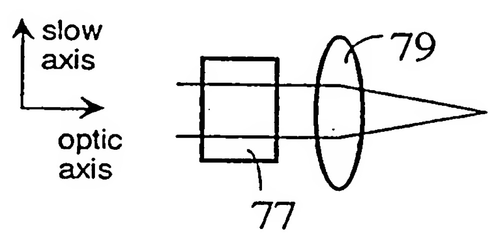

FIG. 10

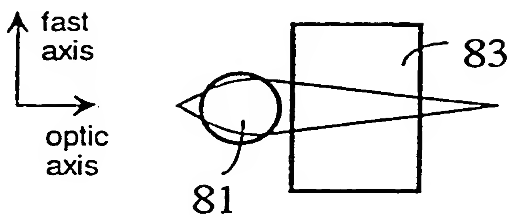

FIG. 11

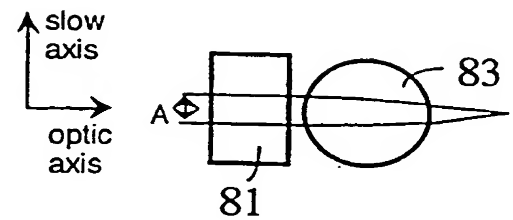

FIG. 12

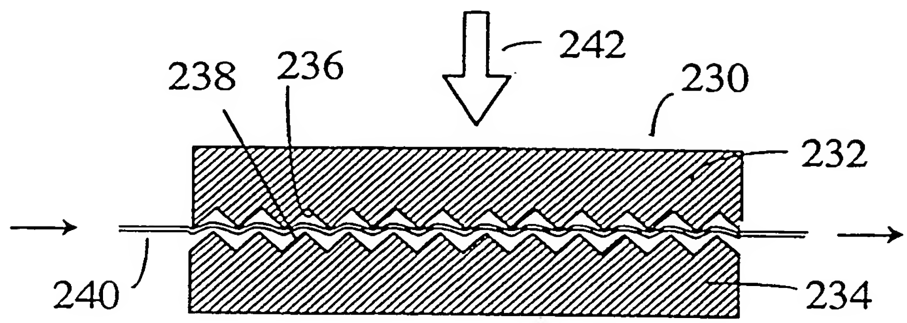

FIG. 29

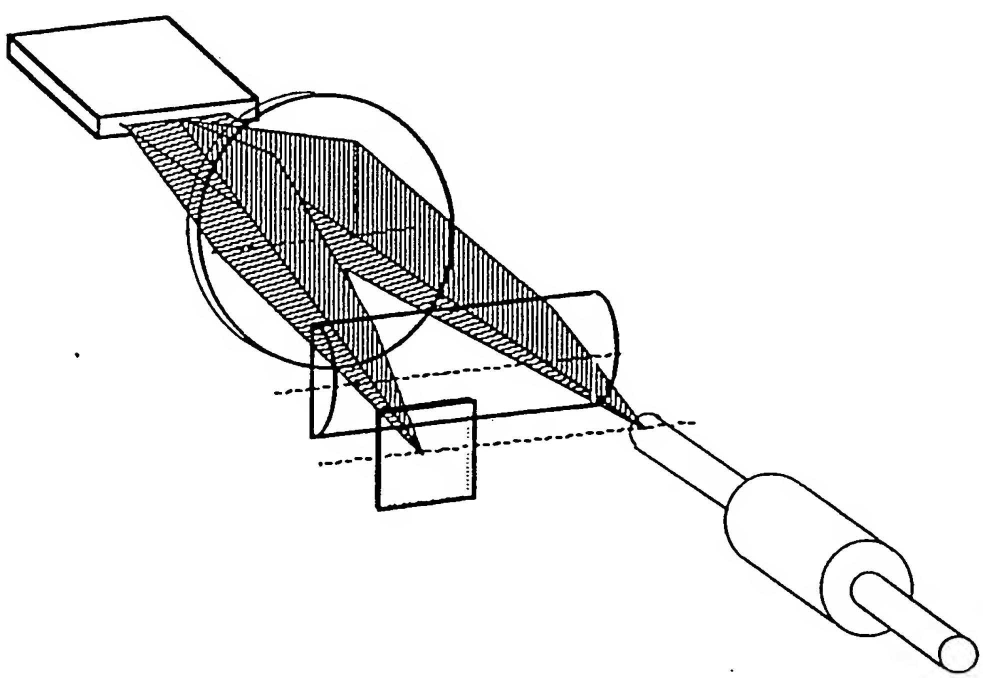

FIG. 13

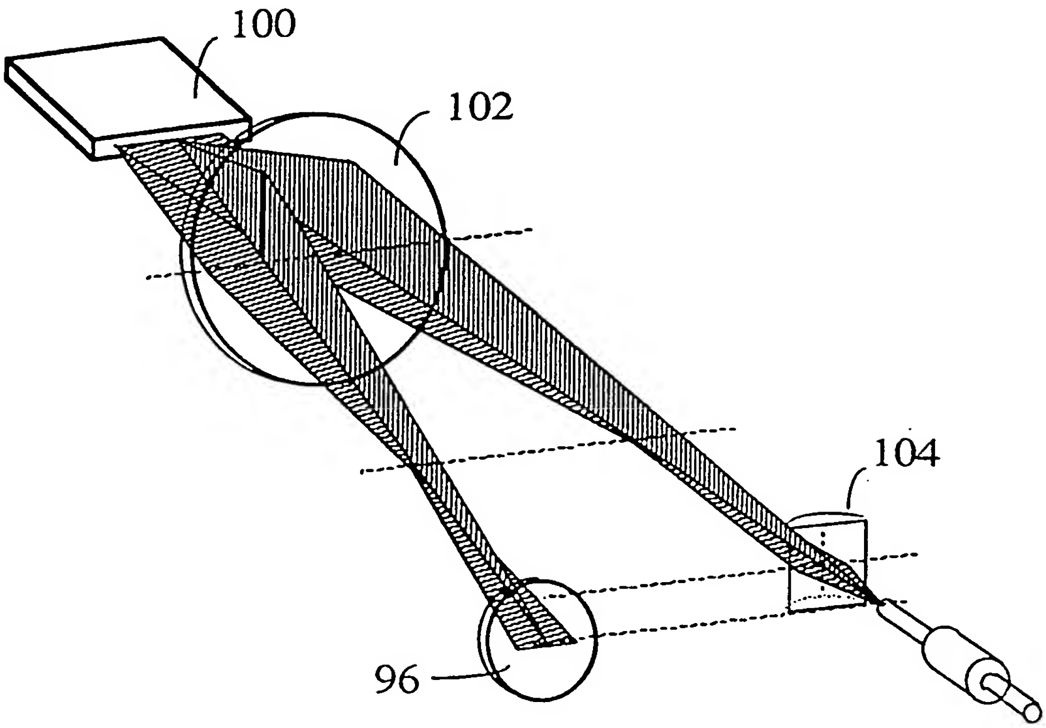

FIG. 14

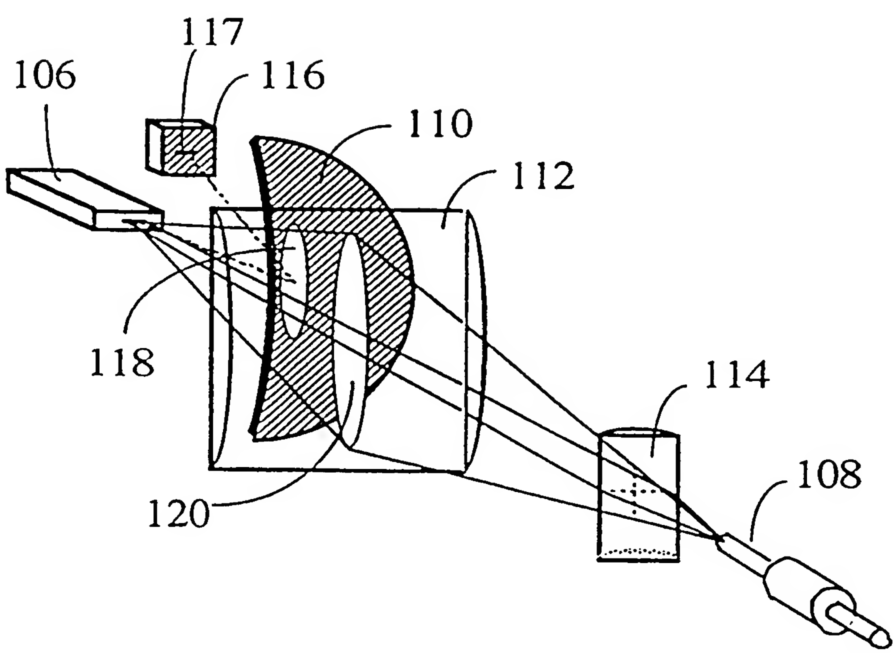

FIG. 15

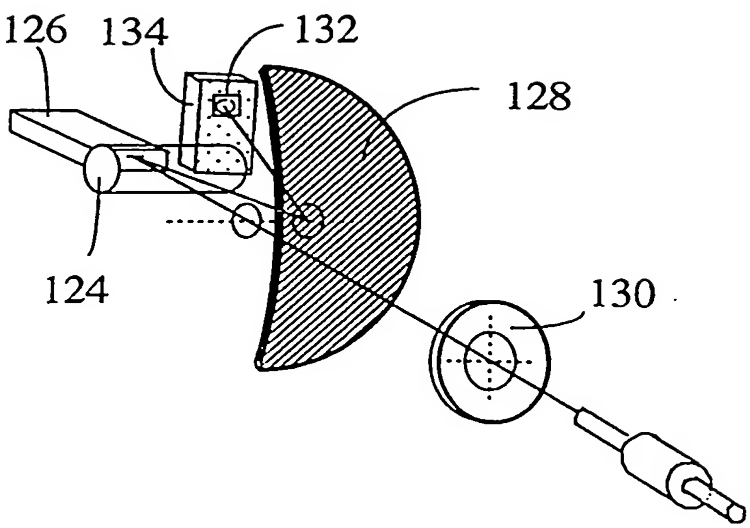

FIG. 16

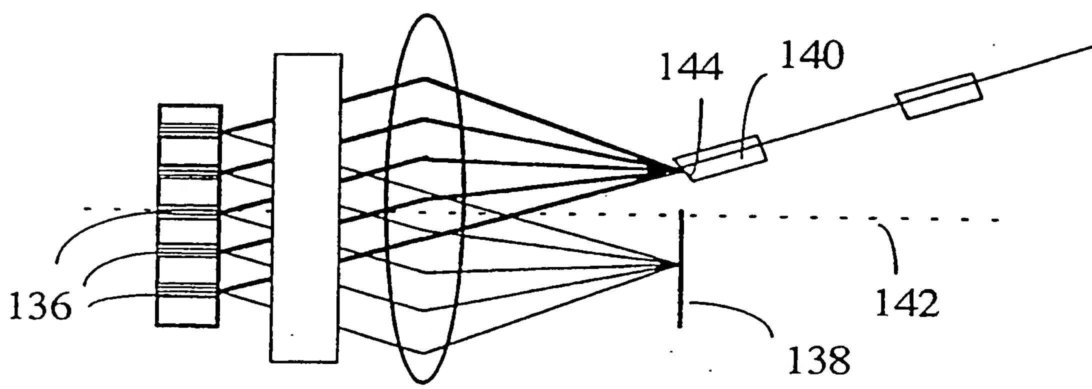

FIG. 17

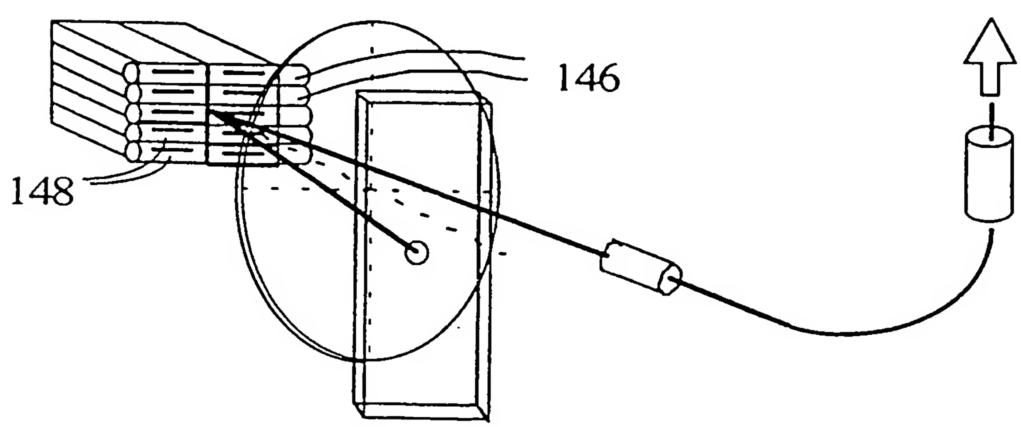

FIG. 18

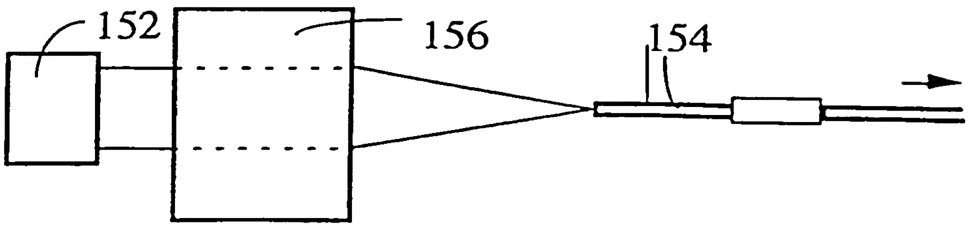

FIG.19

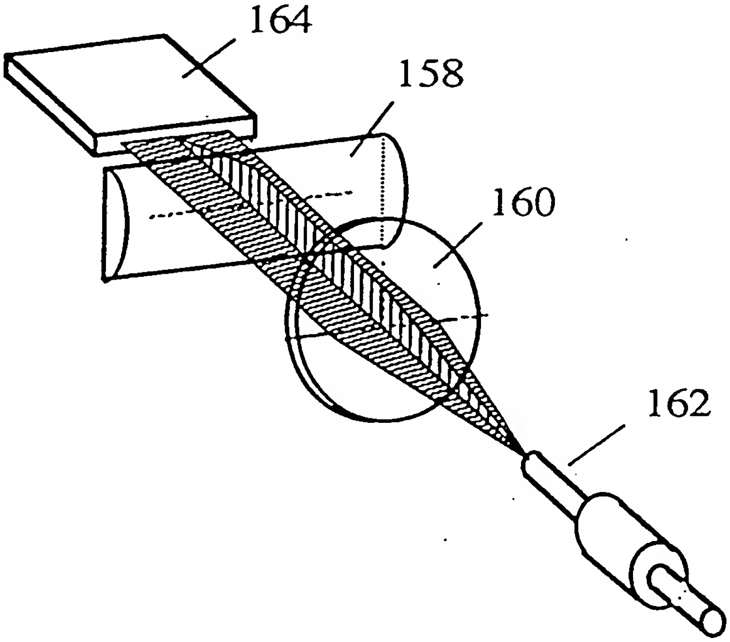

FIG. 20

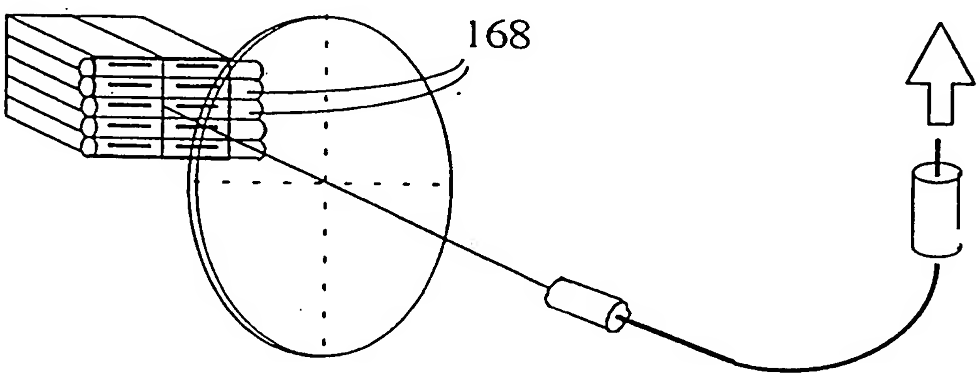

FIG. 21

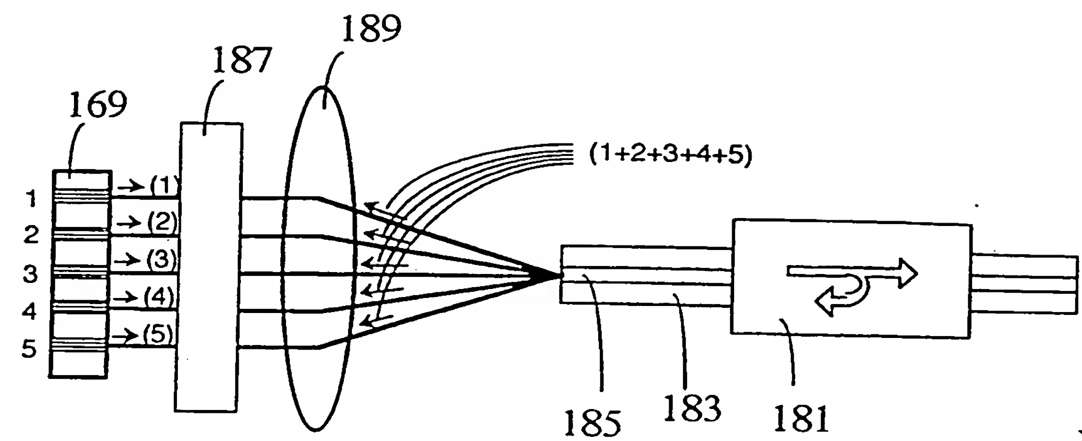

FIG. 21A

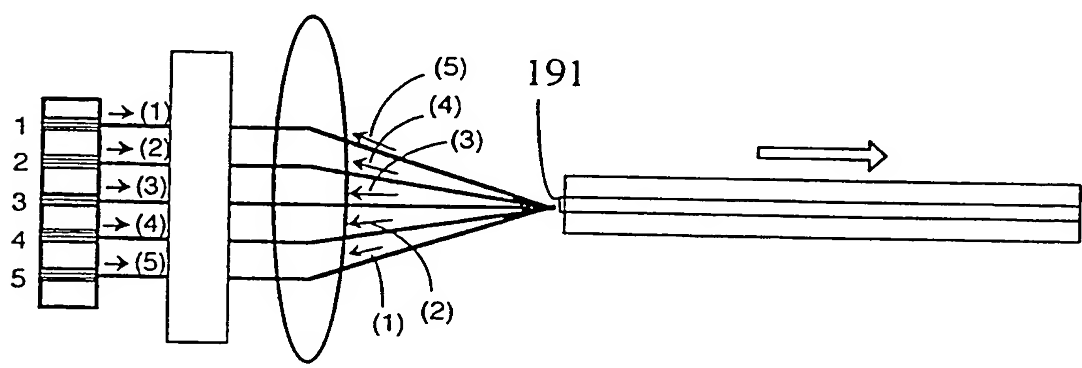

FIG. 21B

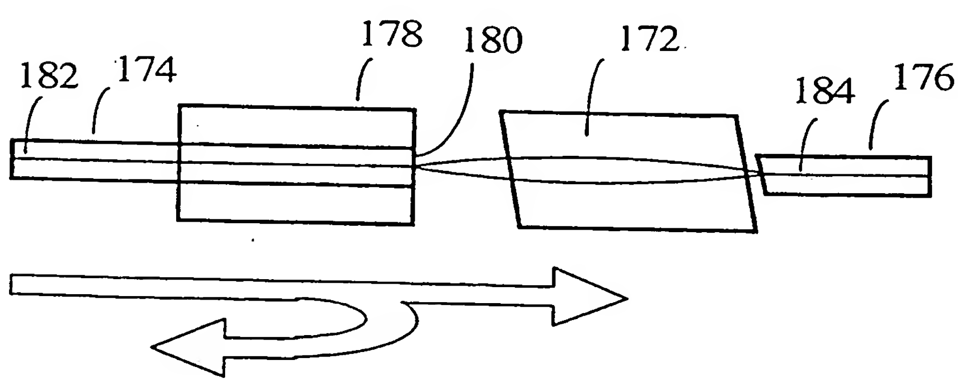

FIG. 22

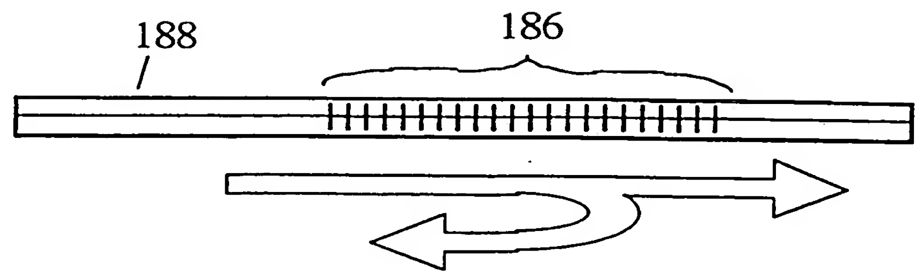

FIG. 23

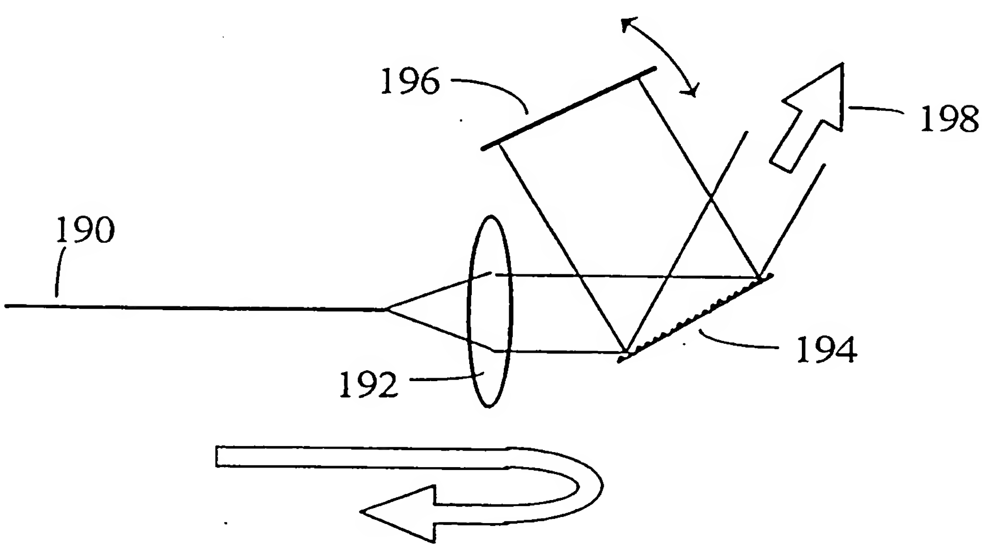

FIG. 24

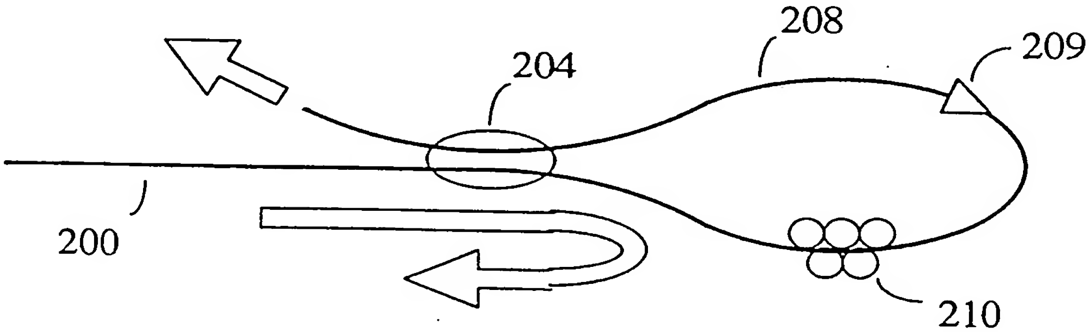

FIG. 25

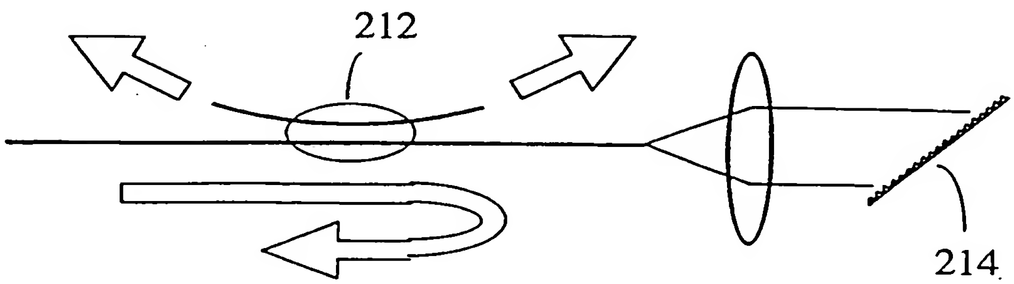

FIG. 26

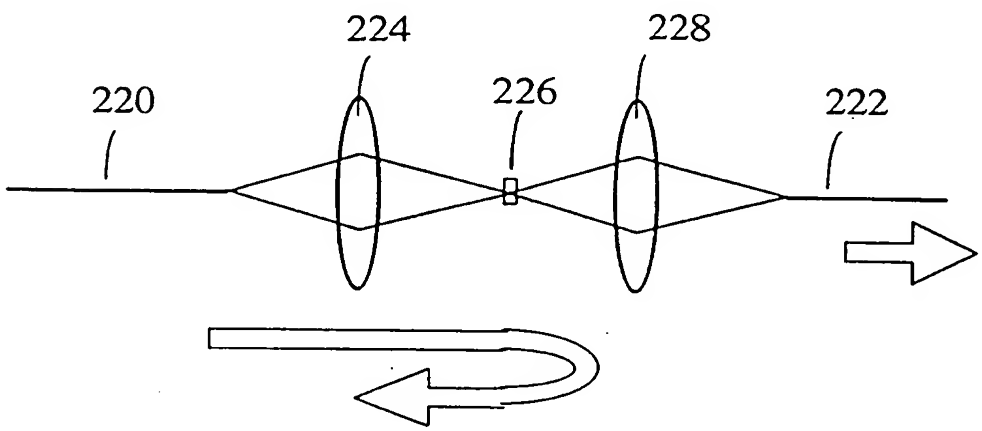

FIG. 27

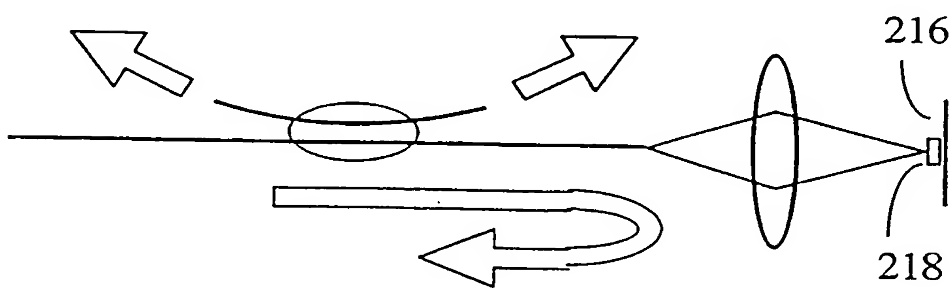

FIG. 28

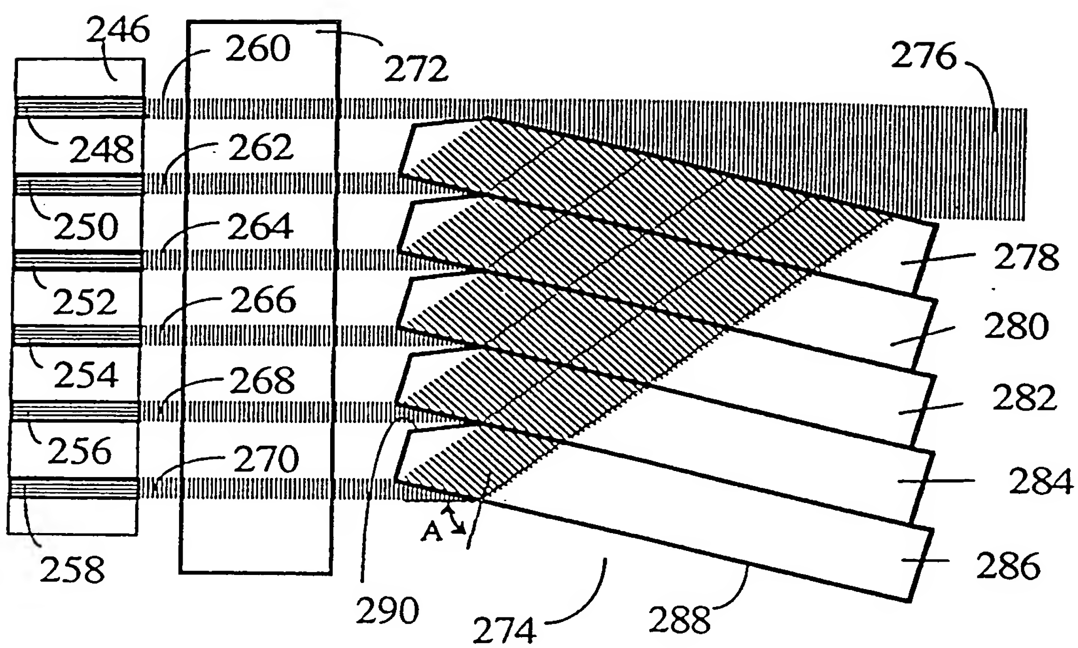
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FIG. 30

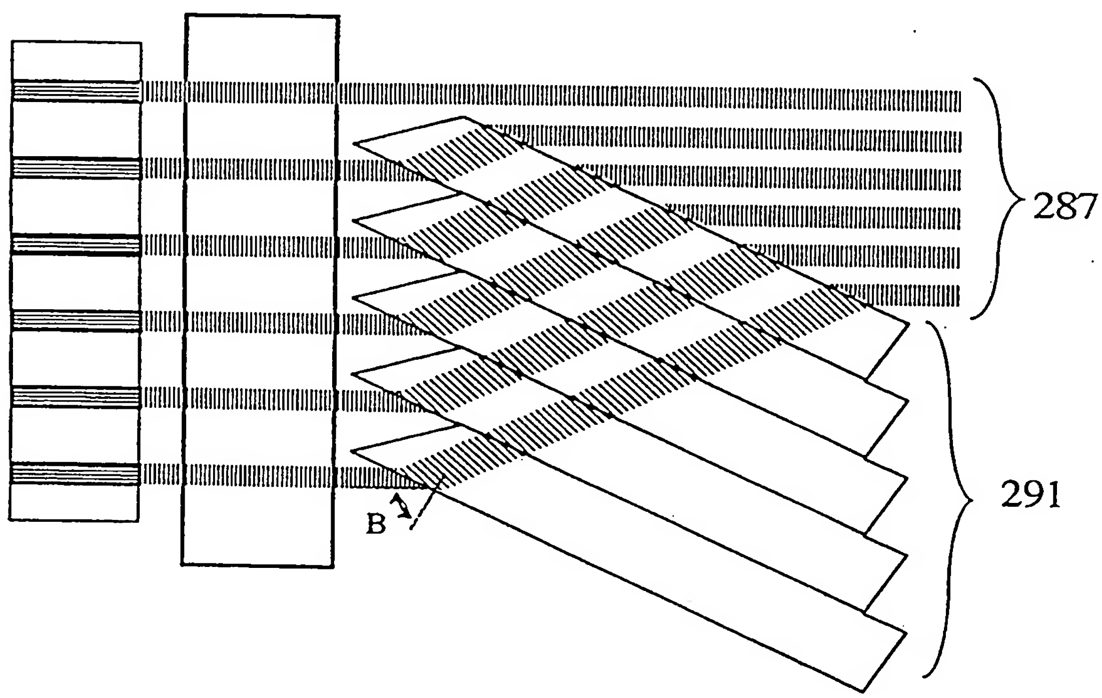
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FIG. 31

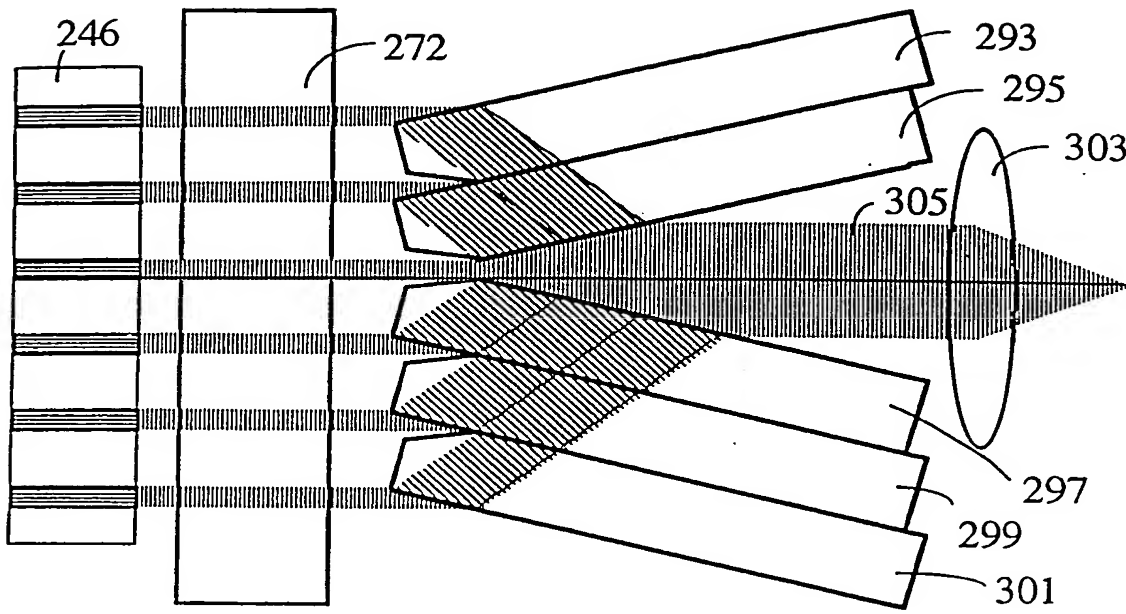
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FIG. 32

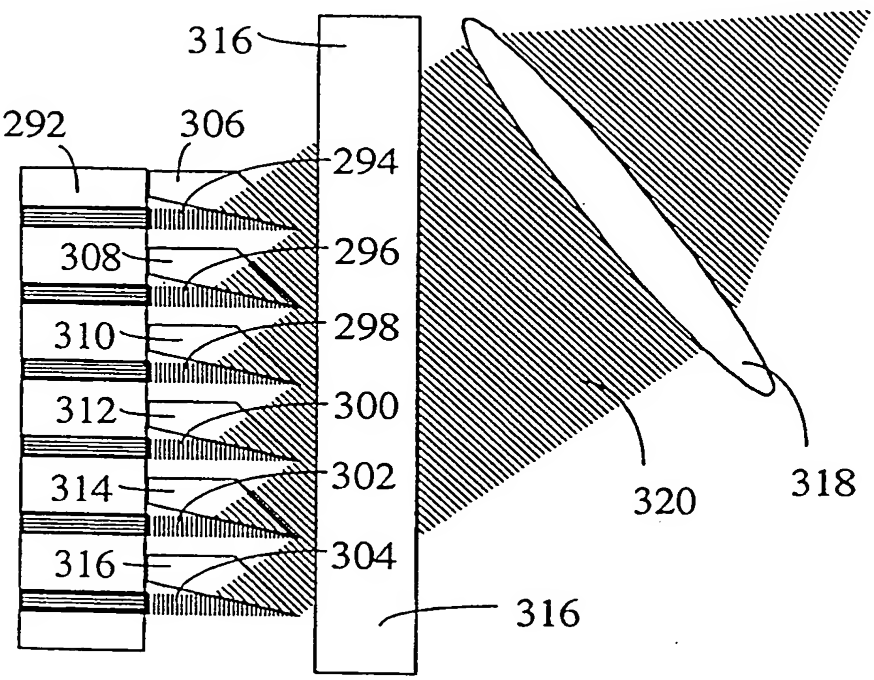
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FIG. 33

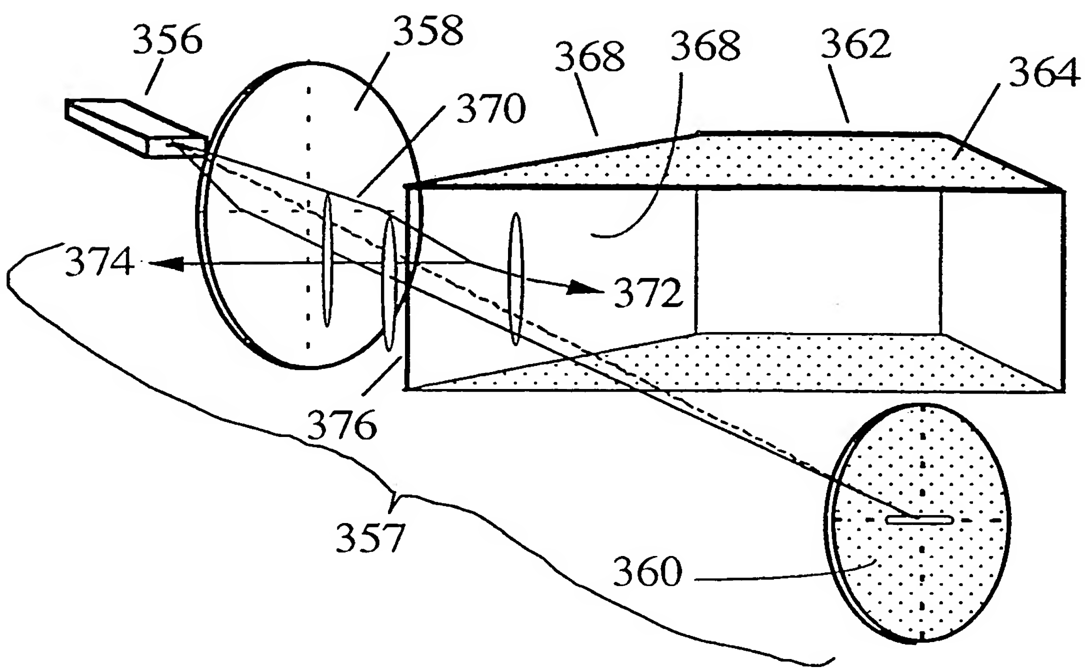

FIG. 34a

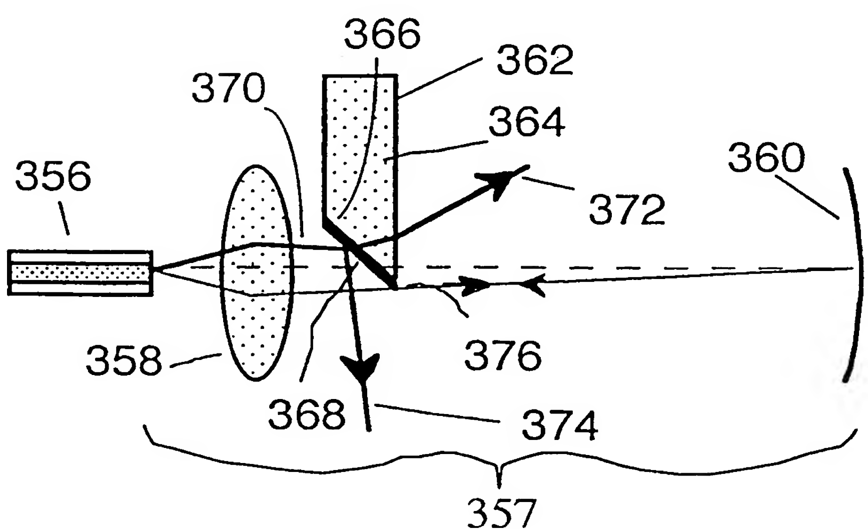

FIG. 34b

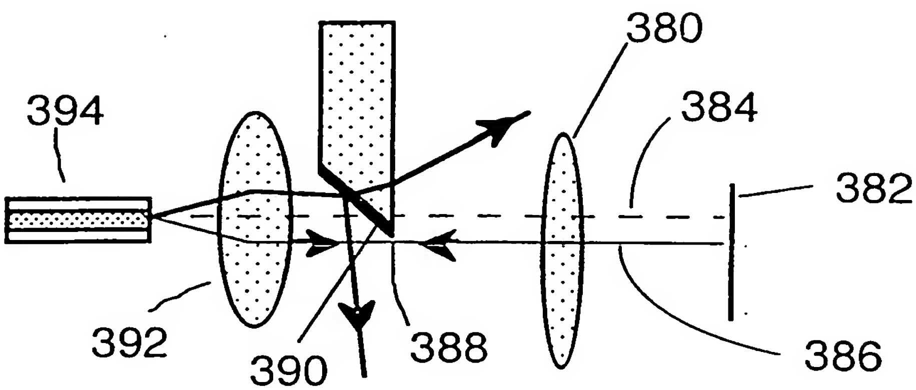

FIG. 35

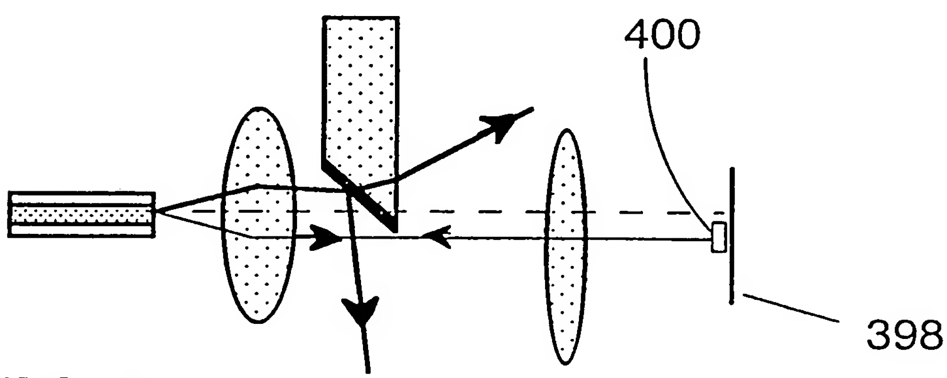

FIG. 36

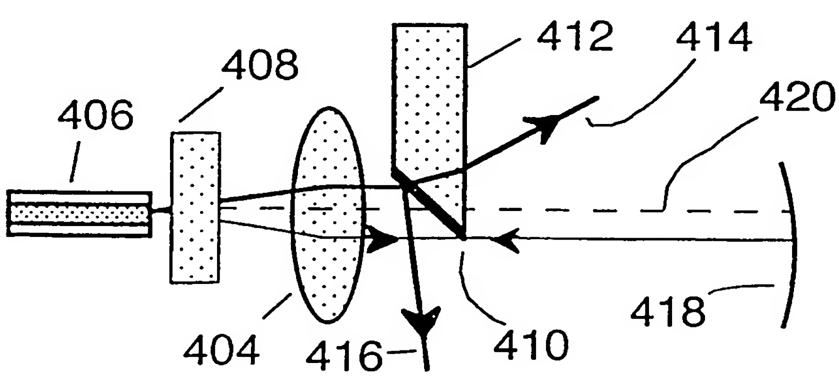

FIG. 37

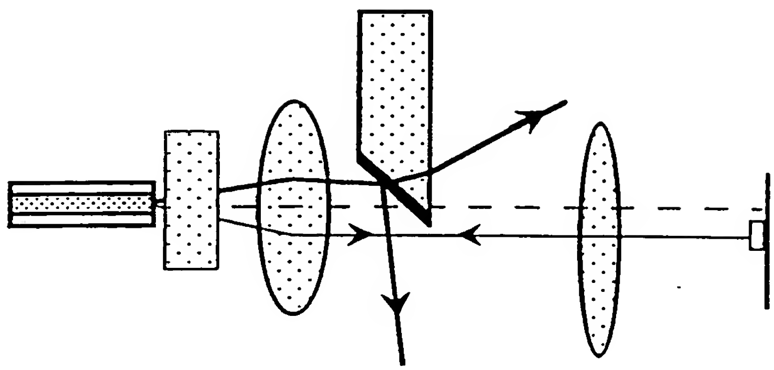

FIG. 38

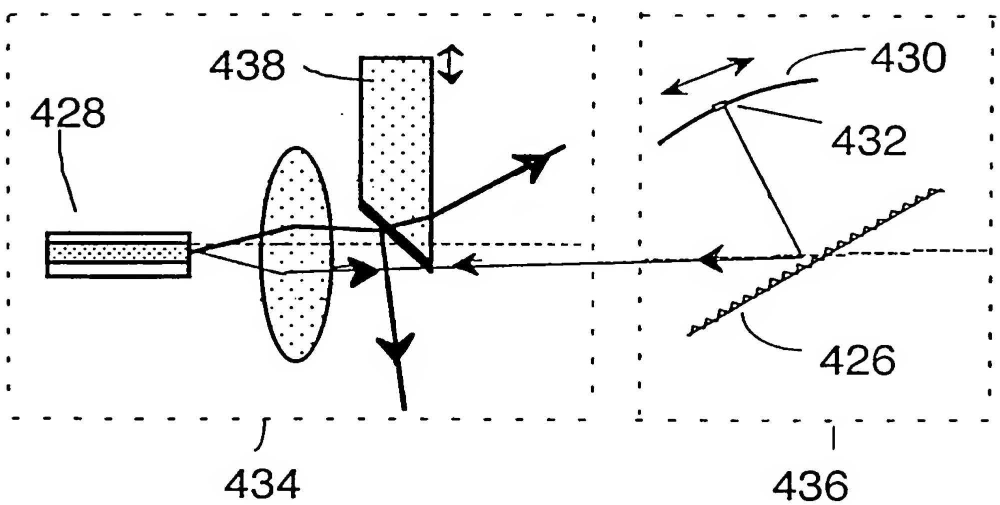

FIG. 39

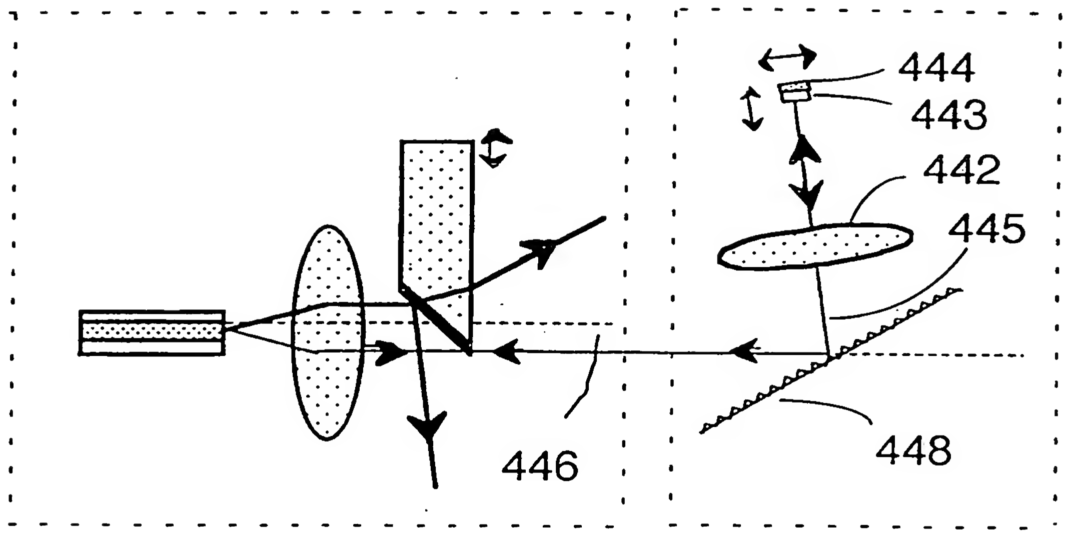

FIG. 40

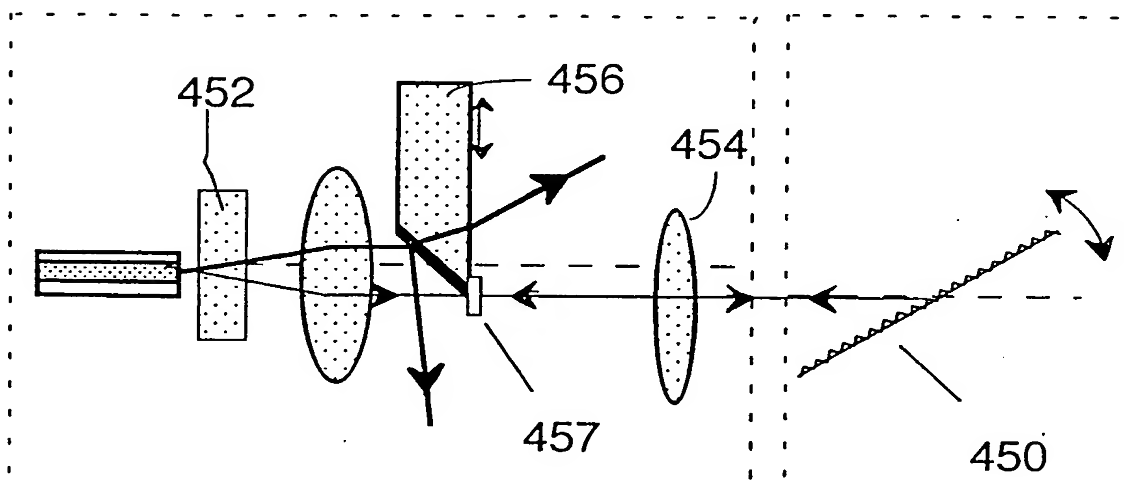

FIG. 41

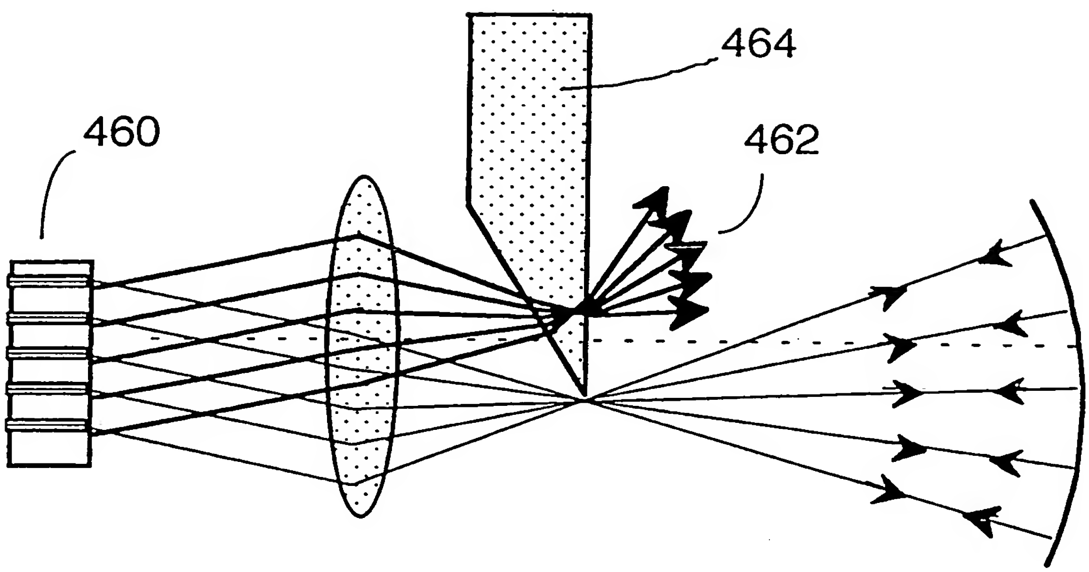

FIG. 42

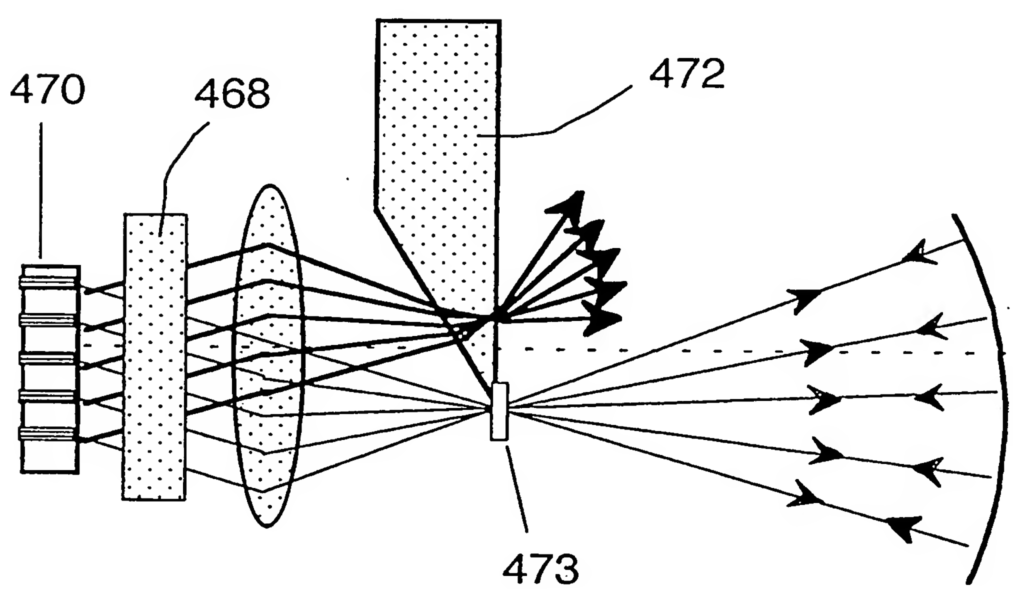

FIG. 43

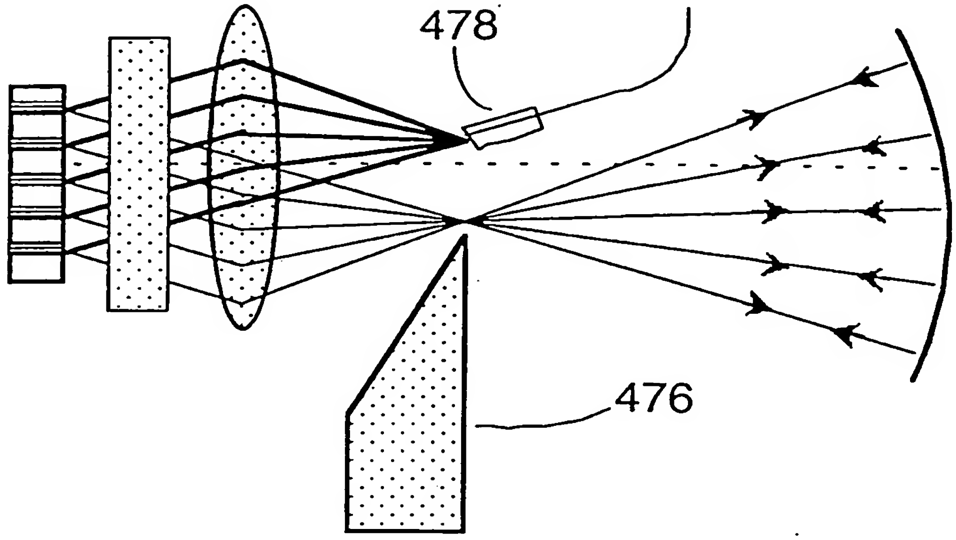

FIG. 44a

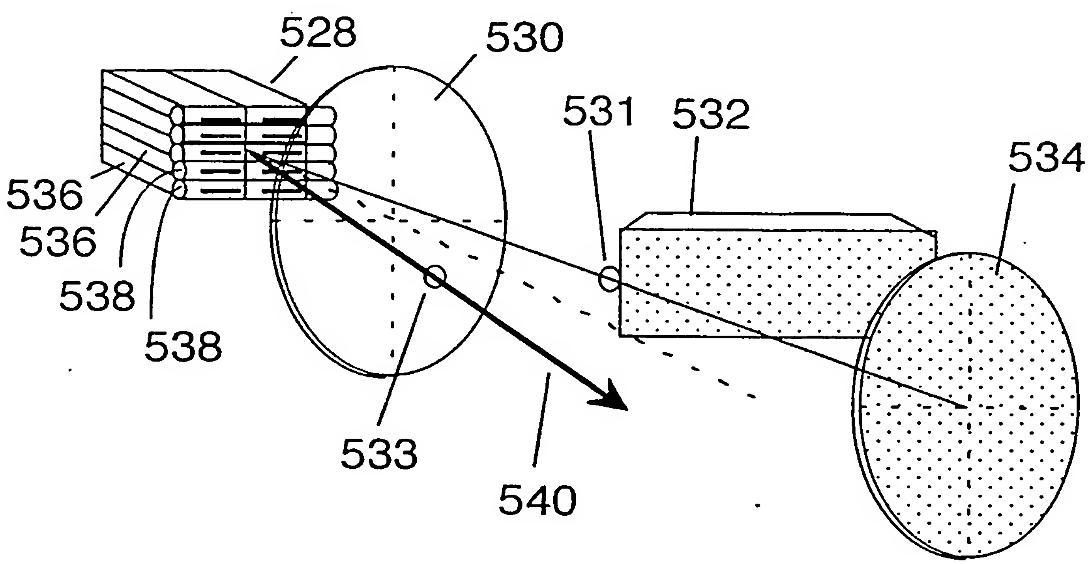

FIG. 44b

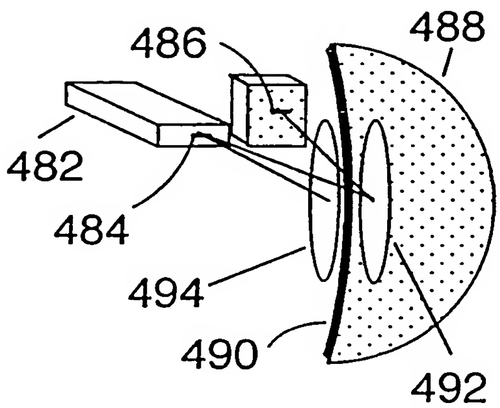

FIG. 45

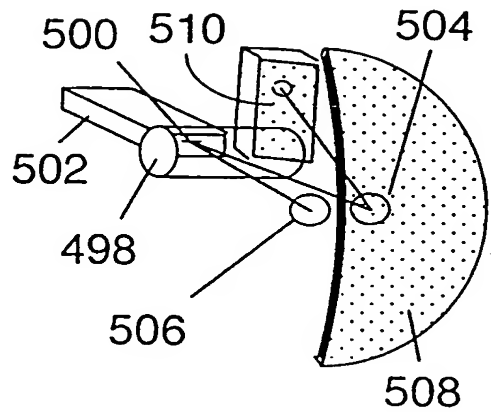

FIG. 46

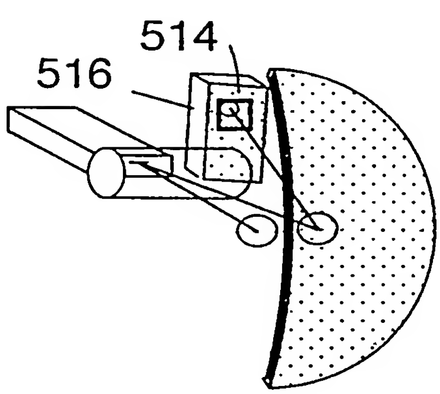

FIG. 47

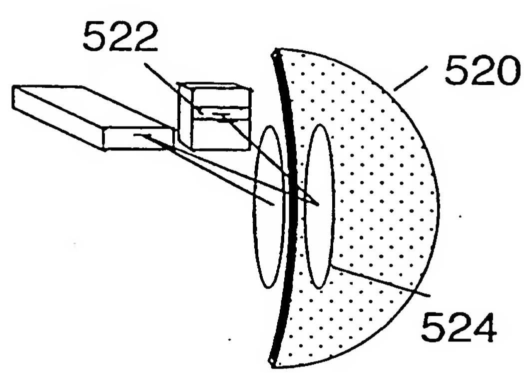

FIG. 48

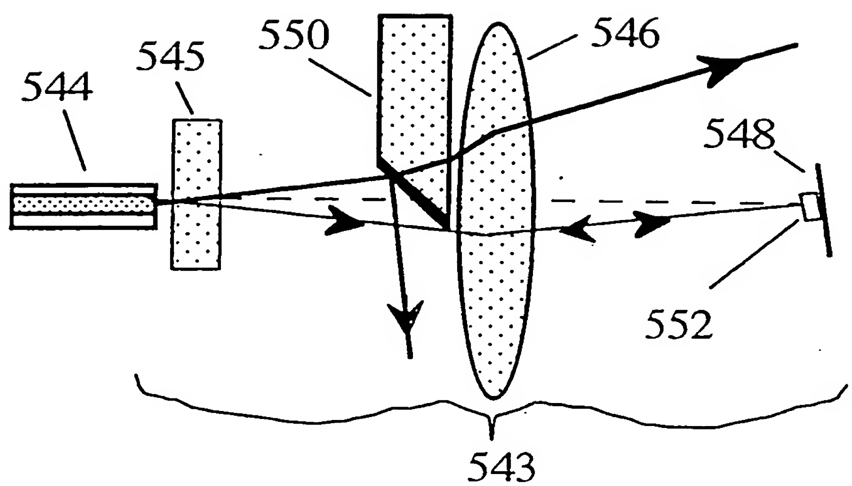

FIG. 49